RFS Activities at INFN Milano-LASA

with Cavity Design Examples – SNS and RIA

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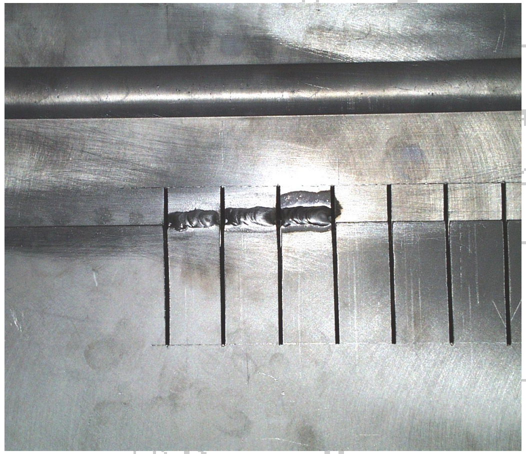
ISTITUTO NAZIONALE DI FISICA NUCLEARE
SEZIONE DI MILANO

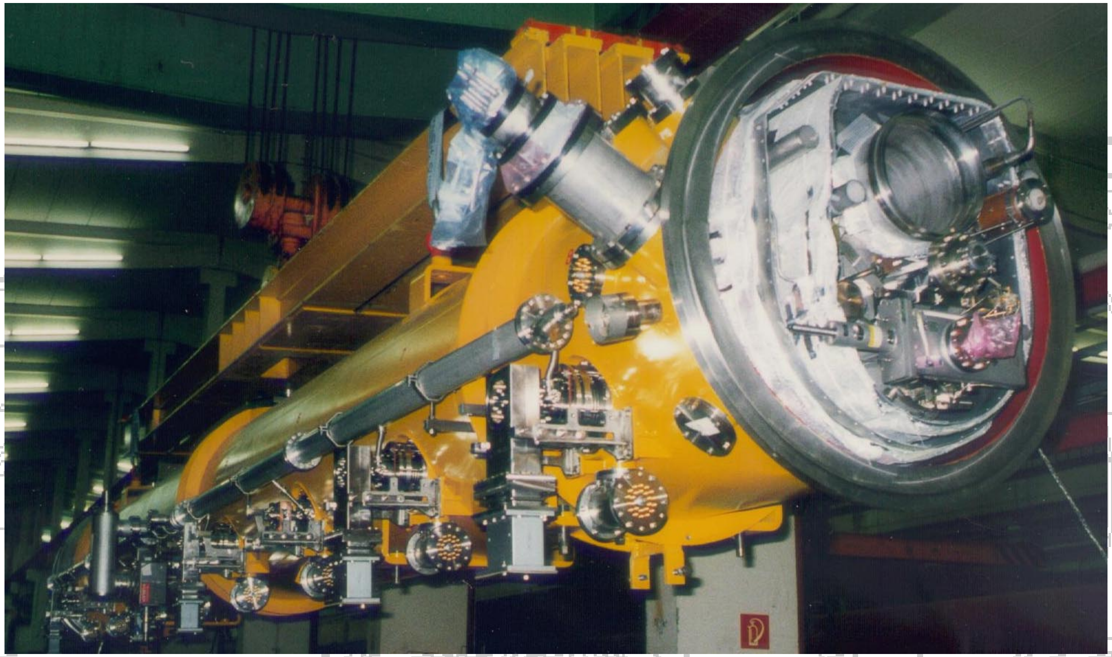
- **TTF/TESLA**
  - **Cryostats for TTF and TESLA**
    - Cryostat design and fabrication (ZANON)
    - Cryomodules assembly
    - Wire Position Monitors - Special internal instrumentation
  - **SC Cavities for TTF** (with ZANON)
  - **Photochathodes for the RF Guns** (and RF Gun Design with FNAL and UCLA)
  - **New Tuner for TESLA?** (we will see)
- **TRASCO -** SC Linac for Nuclear Waste Transmutation
  - **SC linac design** above 85 MeV
  - **Beam dynamics** (new tools and a multi-grid code)
  - **Cavity design** (new cavity design tools)
  - **Cavity prototypes** (at 352.2 and 704.4 MHz)
  - **Cryostat design**
- **SNS and RIA**
  - **Cavity Design** (Collaboration with Jlab - MOU)
  - **SC Linac design** (Collaboration with LANL)
- New Experimental Setup at LASA for SC Cavity Measurements

TTF Cryomodules

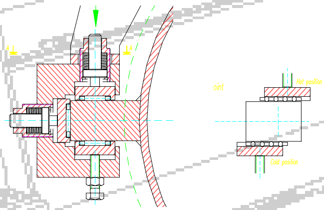
In view of TESLA

"Finger Welded" Shields

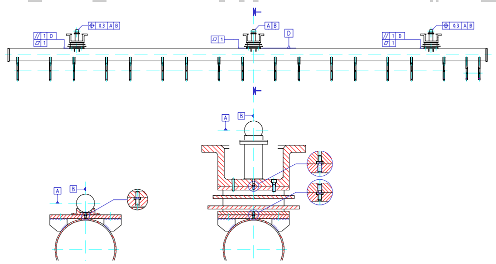




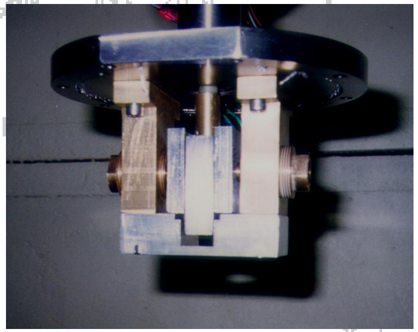
Sliding Fixtures



Allignement Strategy



Sliding Fixtures Qualification



From SNS ASAC Meeting
BLN, December 1999

Efficient Use of the Cavities

Criteria for linac sectioning and choice of cavity β:

5 cell structures represent a good compromise for velocity acceptance and active length per cavity

Most of the cavities operate with a transit time factor of more than 0.95 (efficient use)

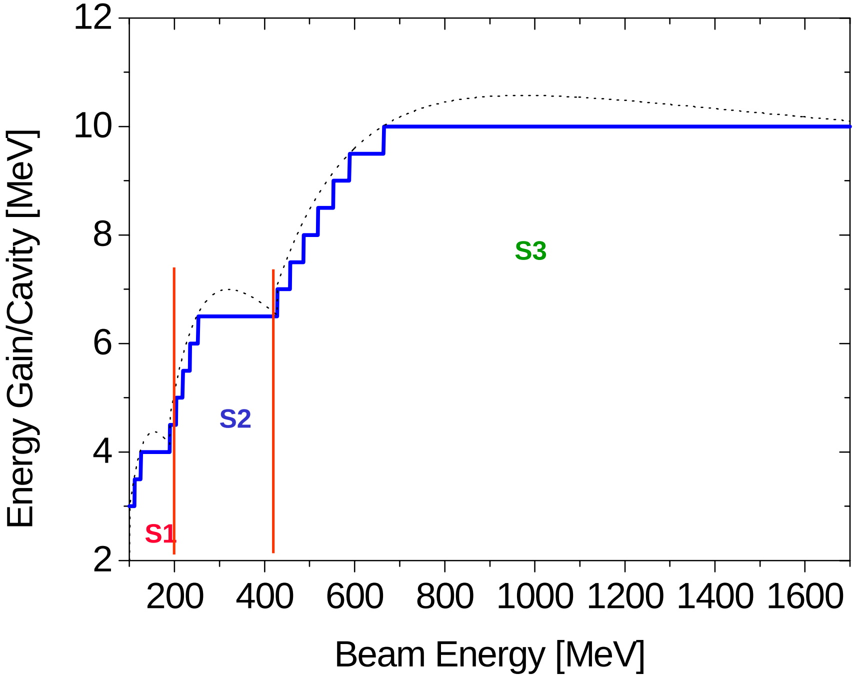
- Only the first modules of each section operate at lower values of the transit time factor (0.80)
- This results in an overall better efficiency for the whole machine

A few cavities in each sections are used for velocity matching by operating them at lower RF power than the rest of the section cavities

This approach allows the totality of each section cavities to operate close to the maximum accelerating gradient

Furthermore, the best RF efficiency is set for the majority of cavities at the end of each section, which operate at a constant energy gain

- constant power consumption per module



Transition energies at 190 MeV and 430 MeV:

S1: 100 ⇒ 190 MeV (β=0.5, i.e. 145 MeV)
S2: 190 ⇒ 430 MeV (β=0.65, i.e. 296 MeV)
S3: 430 ⇒ 1600 MeV (β=0.85, i.e. 843 MeV)

$$x''+k^2x-\frac{\varepsilon^2}{x^3}-const\frac{N}{xz}=0$$

From SNS ASAC Meeting
BLN, December 1999

The Scaling with Frequency

From the envelope equations, simple scaling laws with the design frequency can be derived, allowing to reproduce the same dynamics (scaling properly emittances, currents, and beamline parameters)

higher frequency means physically smaller accelerator components

- ✓ $\Longrightarrow$ divide lengths by a factor 2 (=700/350)
- ✓ $\Longrightarrow$ use a beam physically smaller by a factor 2

keep the same phase advances per period (the basic linac design depends on the choice of the phase advance…)

- ✓ $\Longrightarrow$ the phase advance per meter doubles (the cell size halves!)
- ✓ $\Longrightarrow$ the quadrupole gradients double, the length and bore are halved
- ✓ $\Longrightarrow$ the cavity gradients double

To have the same dynamics we need to divide the emittances by a factor 2

If we also keep the same ratio of the emittance term to the space charge term,

- ✓ $\Longrightarrow$ use the same peak beam current (twice the charge in the bunch)

In this way the envelope equation is formally the same!

Of course, the "boundary" condition at low energy is different for the two frequencies

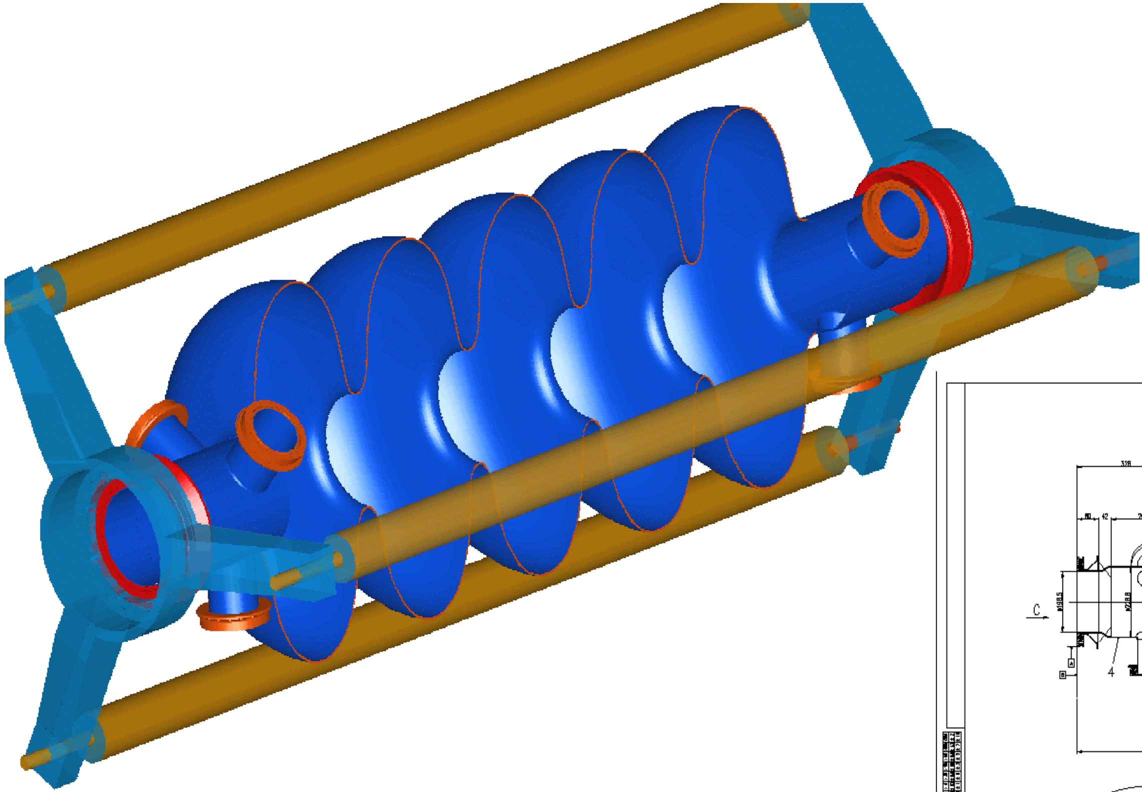
We did not consider the matching to the focusing channel of the previous linac section, which will be obviously different in the two cases due to the frequency transition

TRASCO – Cavity Prototyping

- 350 MHz cavities with CERN
  - Single cell sputtered – $\beta = 0.86$
  - 5 cell sputtered – $\beta = 0.86$
  - Cavity integration in a LEP type cryostat – Under way at CERN
- 700 MHz Cavities with ZANON (+ Saclay & JLab) $\beta = 0.5$
  - One single cell - Built (Zanon) and Tested (Saclay) – RRR>30
  - Three single cells under construction (RRR>30 & RRR>250)
  - One 2-3 cell under design for fabrication optimization and stiffening prototyping
  - One or two 5-cell cavity

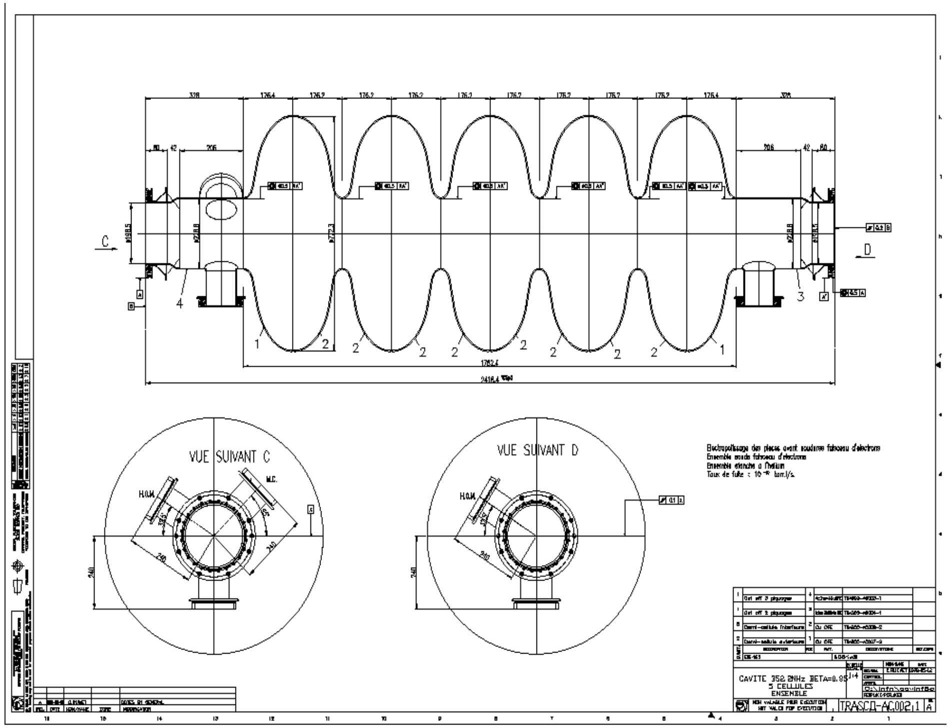
  - Arranging for chemical treatments with a local company (Delmet) – under way
  - Cryogenic RF Test Bench under Commissioning at LASA

TRASCO β=0.85 Cavity Developed with CERN



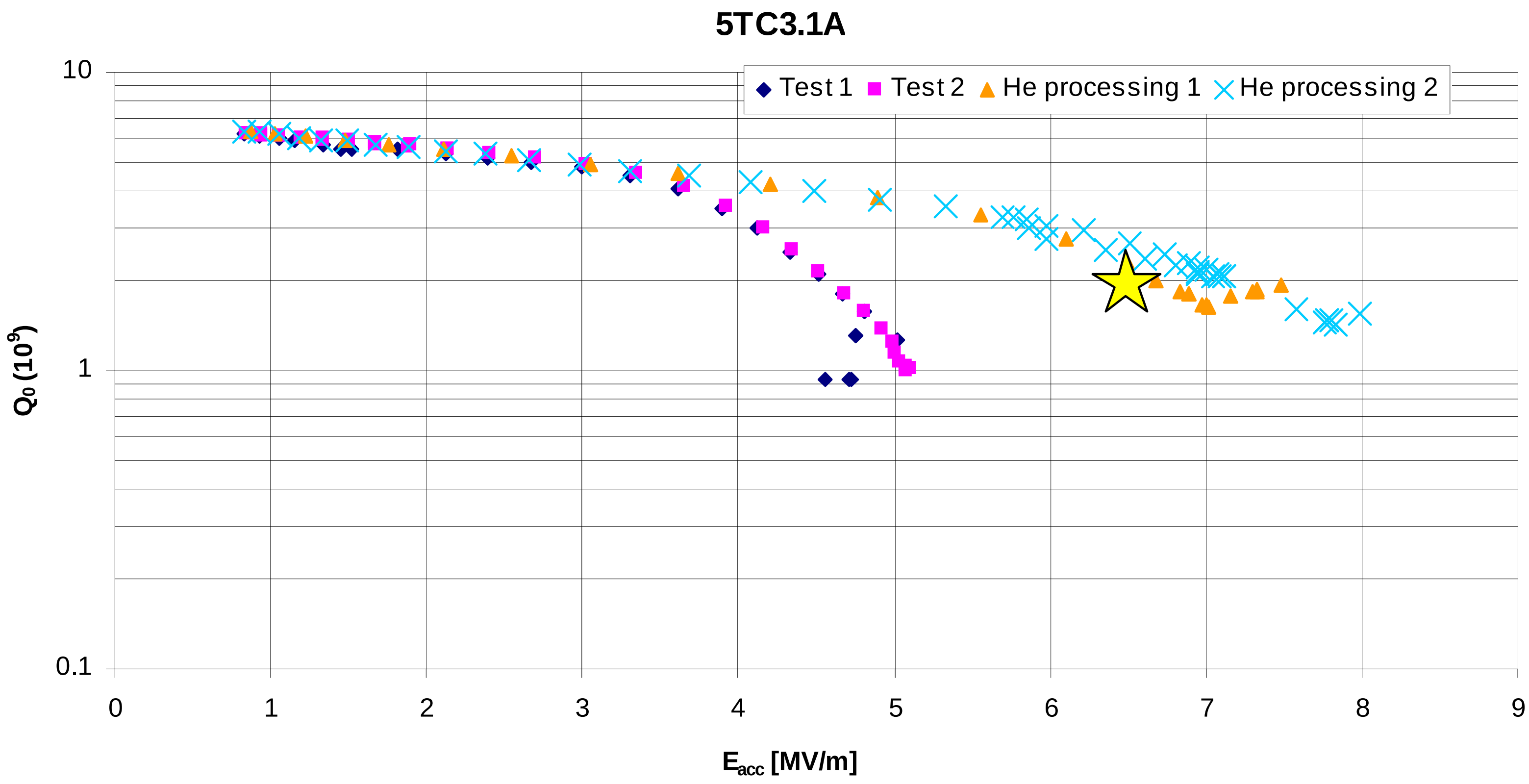
The β=0.85 Nb sputtered on copper cavity has been fabricated at CERN according to our design

The cavity has been tested in May 99



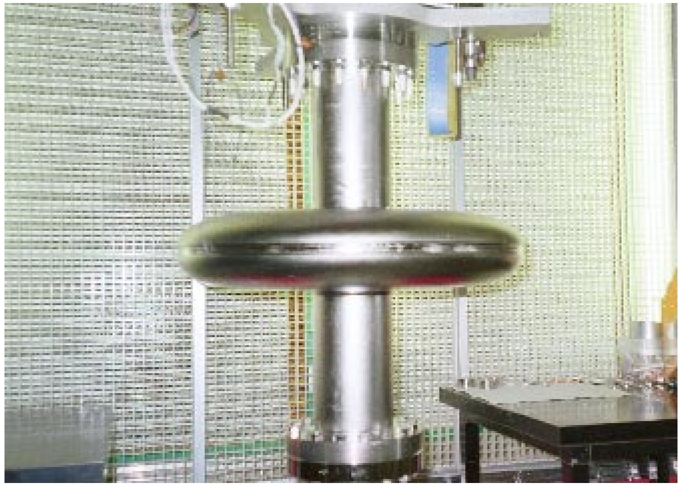
Standard CERN components (flanges, cutoff tubes, coupler port and tuning system) have been used for the tests performed at CERN

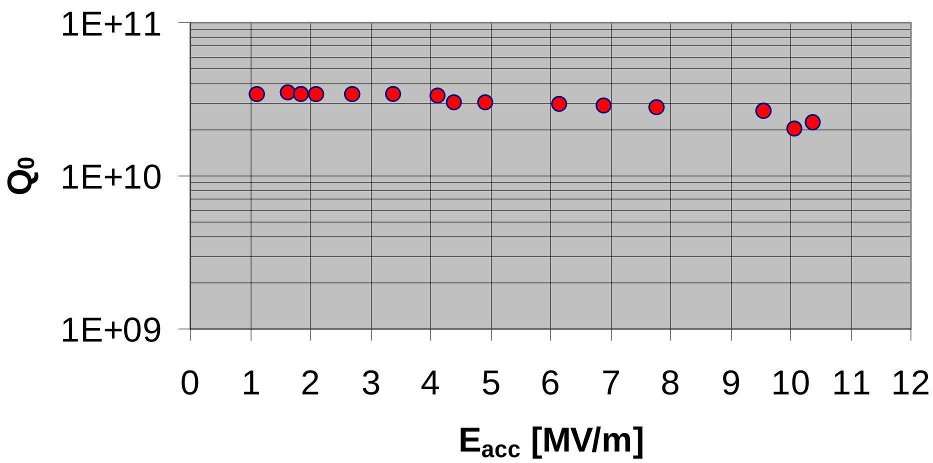
TRASCO-CERN β=0.85 Cavity Results at 4.5 K
Q_o vs. E_{acc} plot (352.2 MHz - 5 cells)

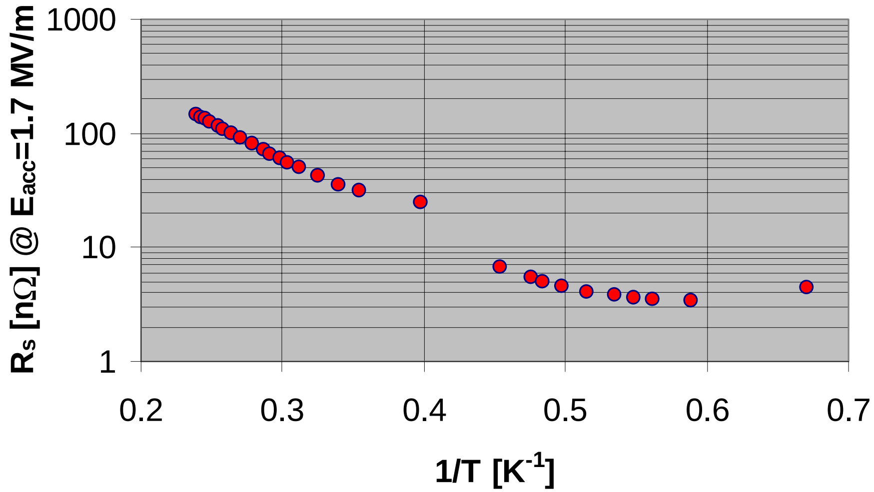


TRASCO 700 MHz: β=0.5 – Single-cell Prototype

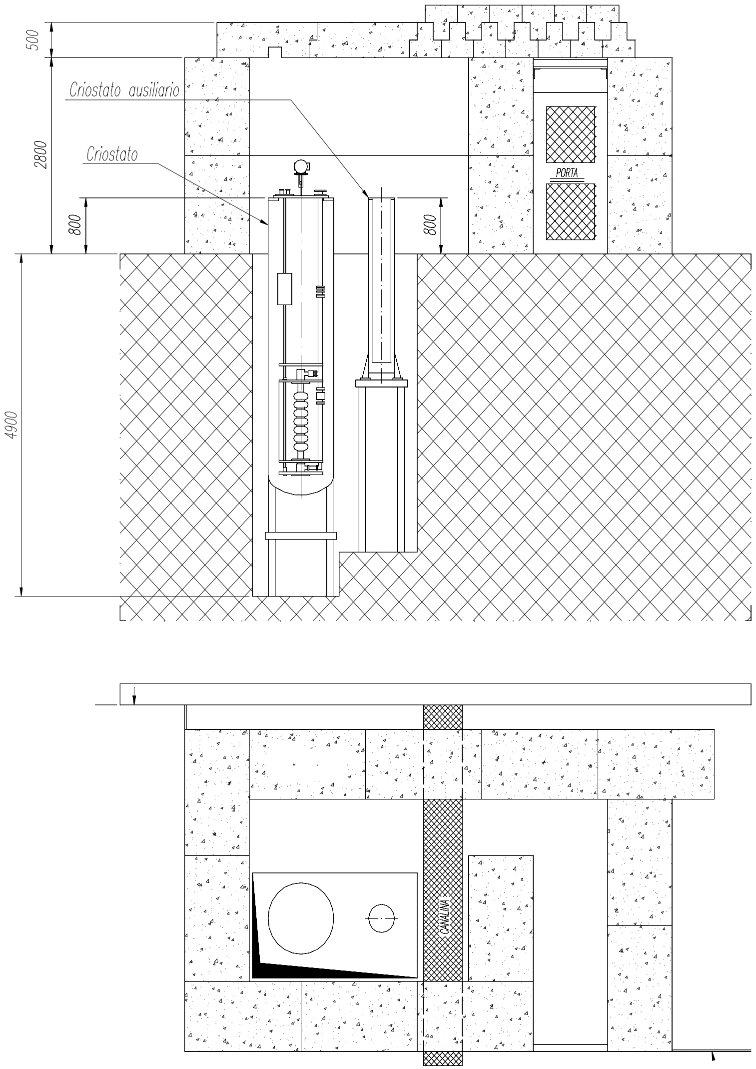
- Fabricated with Reactor Grade (RRR>30) Niobium at ZANON
- Chemical Treatment and HPR at Saclay (no heat treatment)
- Tested at Saclay at 1.5 K

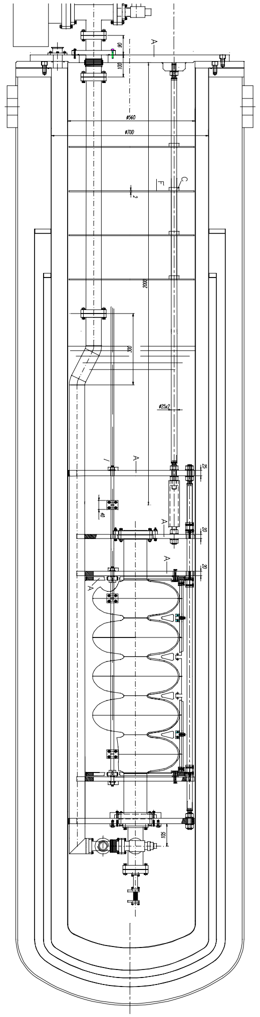






SC RF Cavity Test Facility at INFN Milano-LASA





The new insert with a 5 cell cavity at $\beta = 0.65$

Commissioning of the SRF cold test apparatus

SC Cavity design – The SNS and RIA Examples

- The number of possible parameters involved in the design of a SC cavity is big and, without a proper choice of parametrization, it can be hard to correlate a single geometrical parameter to the electromagnetic and mechanical performances of the cavity

- The number of possible different strategies for the cell tuning can complicate the correlation process

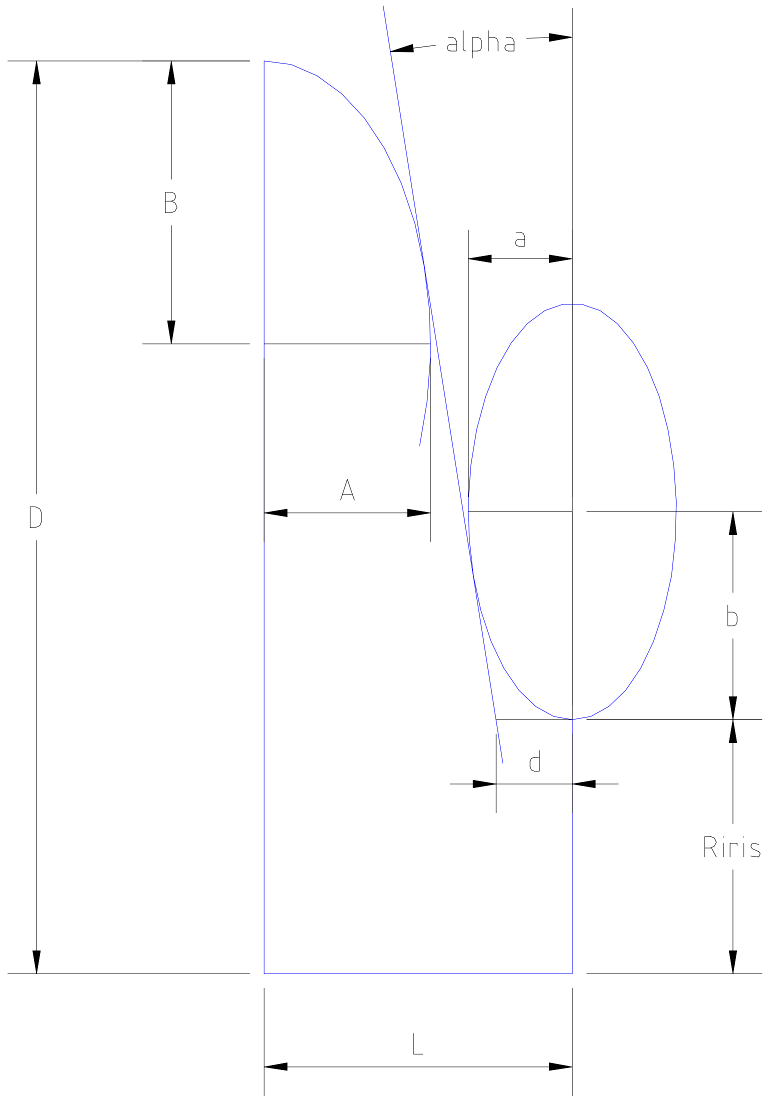
- A suitable parametrization and tuning strategy helps to rule more easily the cavity performances, including the mechanical aspects

- Since SNS cavities have unique performance requirements with respect to existing cavities operating in accelerators, we also need to be "open-minded", avoiding the choice of pre-digested design strategies guided by existing cavity design tools

From SNS CCS Workshop
TJNAF, April 2000

Cell Shape Parametrization

- Full parametric model of the cavity in terms of 7 meaningful geometrical parameters:
  - ✓ Ellipse ratio at the equator (R=B/A)
    Ruled by Mechanics
  - ✓ Ellipse ratio at the iris (r=b/a)
    Epeak
  - ✓ Side wall inclination (α) and position (d)
    Epeak vs. Bpeak tradeoff and coupling k
  - ✓ Cavity iris radius R_{iris}
    Coupling k
  - ✓ Cavity Length L
    β
  - ✓ Cavity radius D
    used for frequency tuning
- Behavior of all e.m. and mechanical properties has been found as a function of the above parameters



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Tools used for the parametrization

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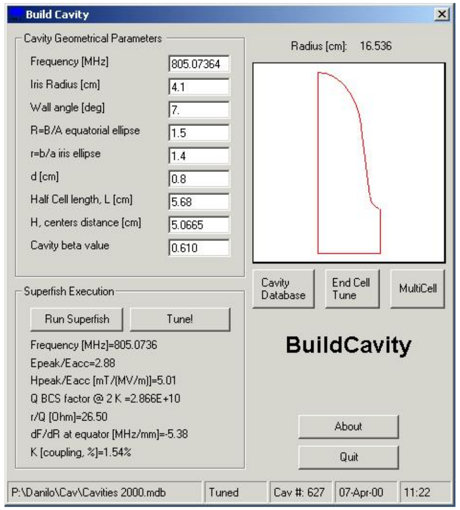
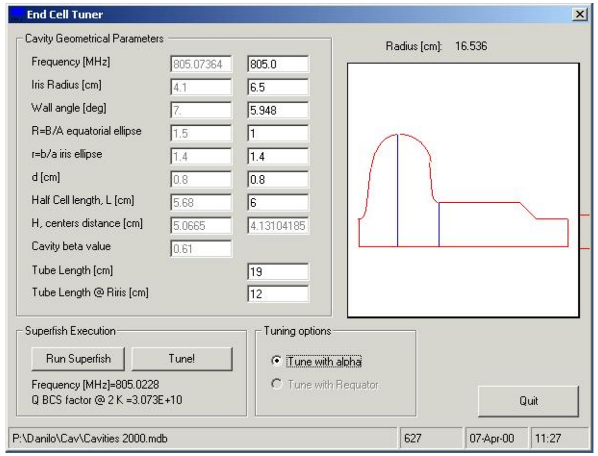
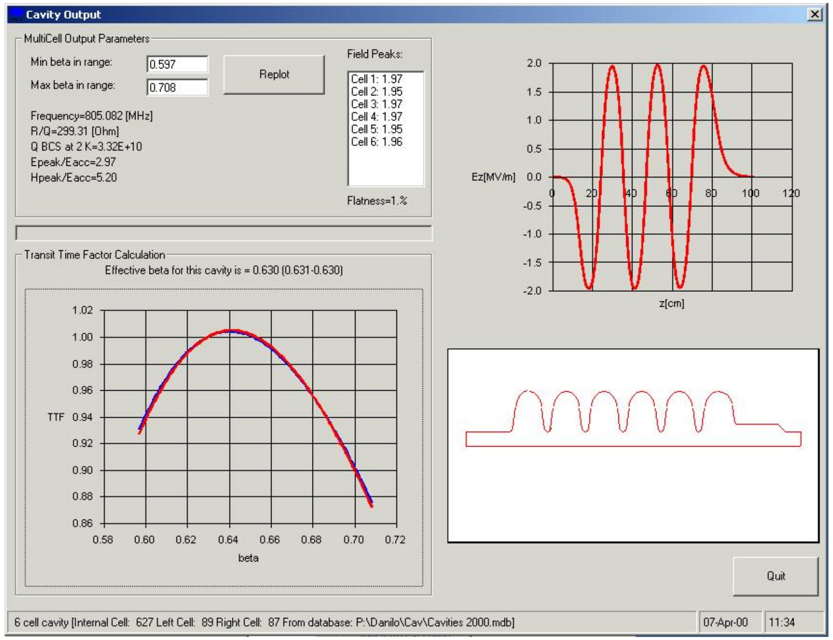
- We built a parametric tool for the analysis of the cavity shape on the electromagnetic (and mechanical) parameters
  - All RF computations are handled by SUPERFISH
  - Inner cell tuning is performed through the cell diameter, all the characteristic cell parameters stay constant: R, r, α, d, L, Riris
  - End cell tuning is performed through the wall angle inclination, **α**, or distance, **d**. R, L and Riris are independently settable.
- All e.m. cavity results are stored in a database for futher parametric investigations.
- A multicell cavity is then built to:
  - minimize the field unflatness
  - compute the effective β
  - Compute the final cavity performances
- A proper file to transfer the cavity geometry to ANSYS is then generated





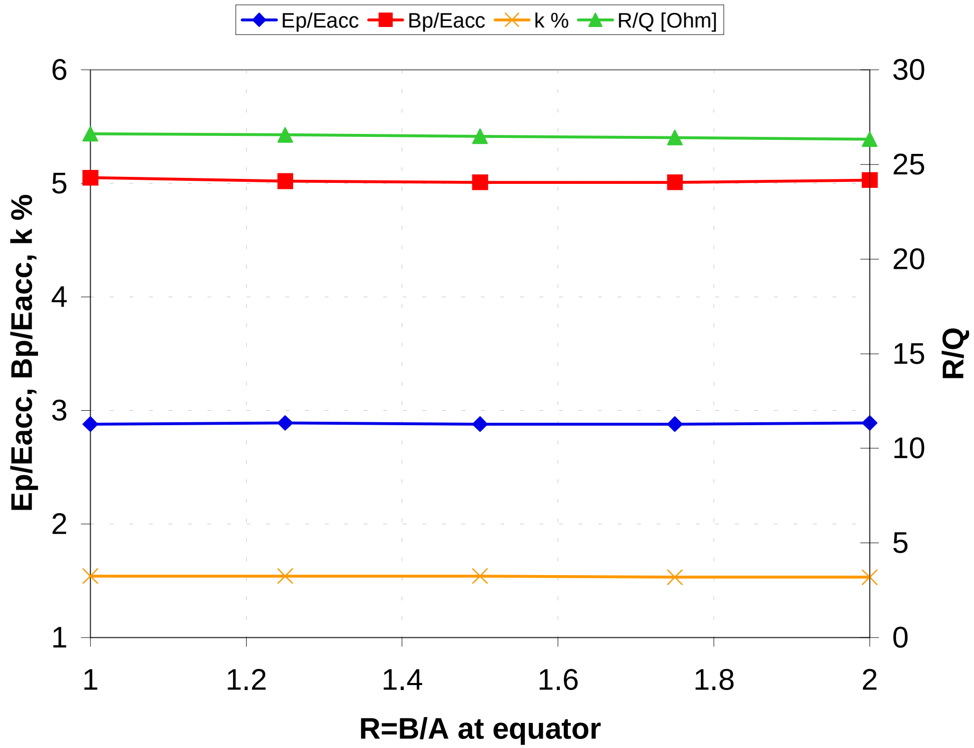


Inner cell data

L = 56.8 mm
R = 1.5
r = 1.4
α = 7°
d = 8 mm
R_{iris} = 41 mm

Freedom to choose R freely...

- The equator aspect ratio (R) is a free parameter for what concerns the π-mode e.m. design
- It can be left open for mechanical and tunability considerations:
  - Mechanical stability
  - Lorents forces detuning
  - Vibration eigenfrequencies
  - End cell tunability
- All the π-mode electromagnetic parameters are not sensible to R
- Due to the tuning strategy the different geometries are just Slater compensated in the equator region
- The further use of R to shift an eventual critical HOM is possible.

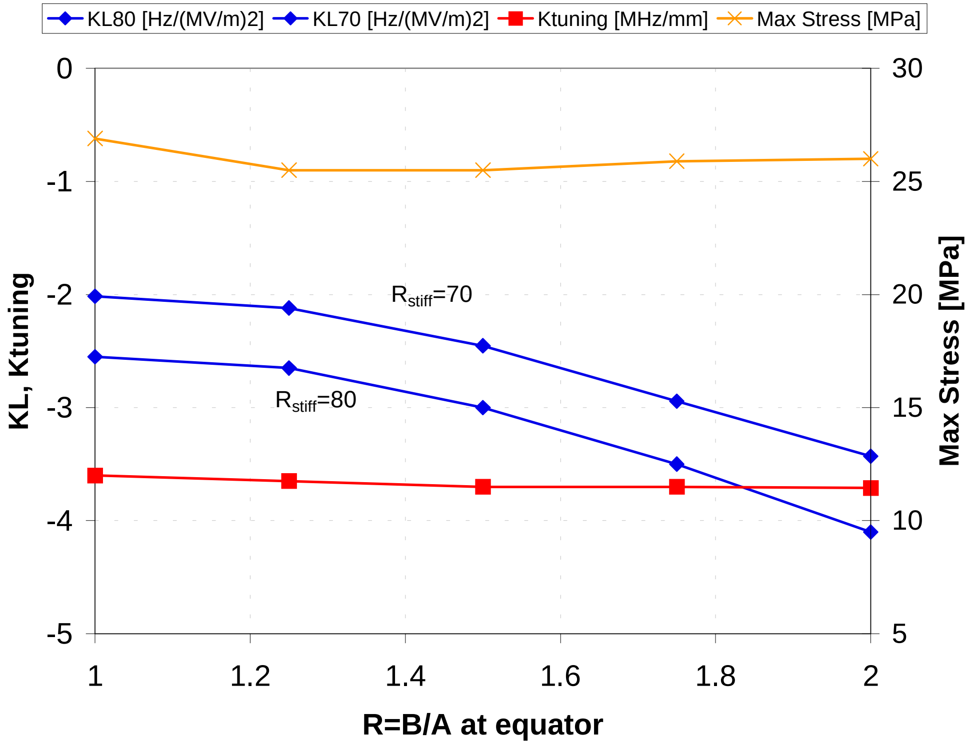


Reference data

L = 56.8 mm
r = 1.4
α = 7°
d = 8 mm
R_{iris} = 41 mm

... but for mechanics considerations

- The cavity mechanical parameters are greatly affected by the equator shape
- Here we display:
  - Lorentz forces coefficient, KL [Hz/(MV/m)^2] for the stiffened cavity (near-optimal stiffening ring radius, see later)
  - Tuning sensitivity coefficient, Ktuning (in terms of MHz frequency variation per one millimiter cavity shortening)
  - Max von Mises stress [MPa] for the stiffened cavity
- R>1 allows a better stress distribution in the unstiffened cavity, but a bigger Lorentz force coefficient

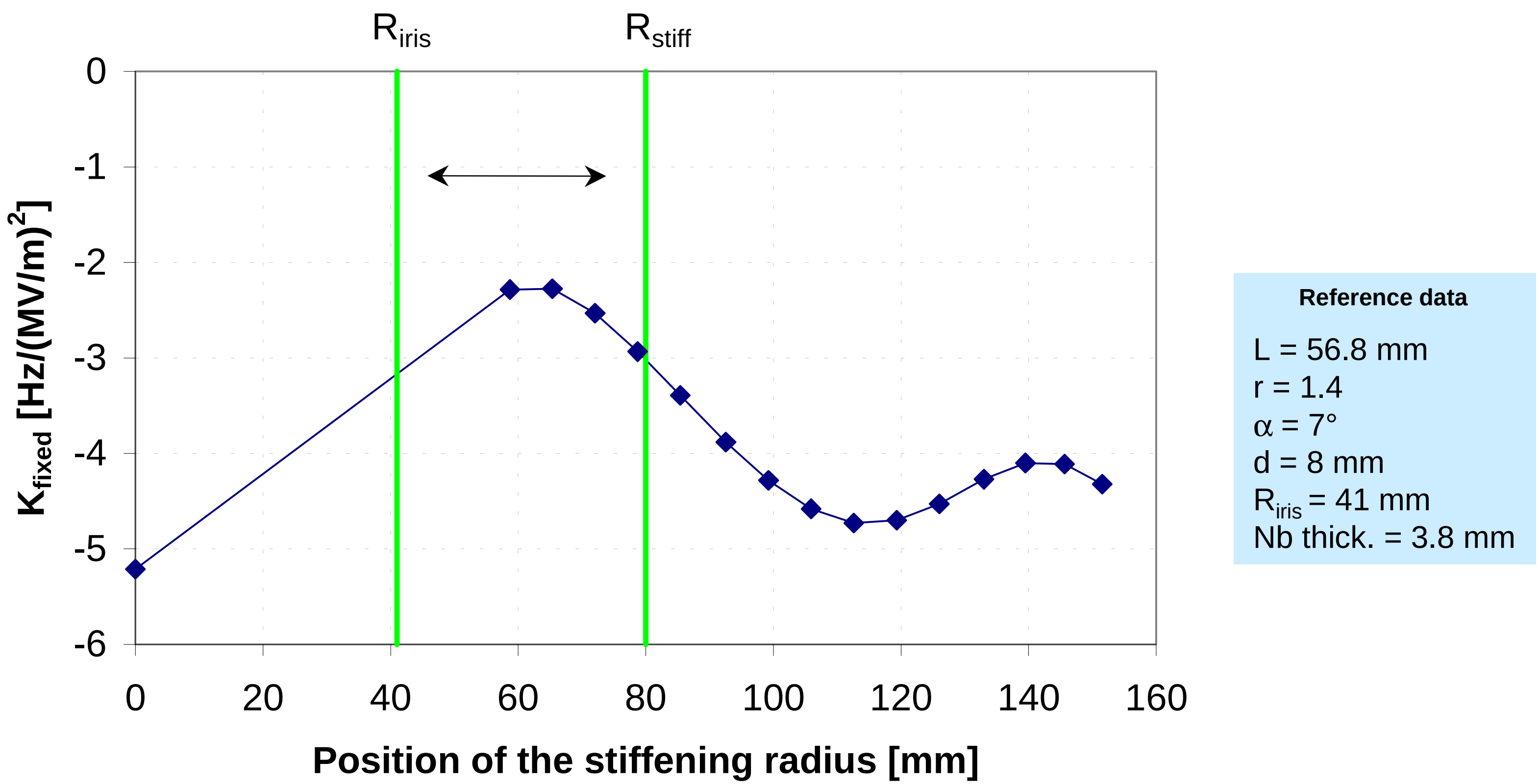


Reference data

L = 56.8 mm
r = 1.4
α = 7°
d = 8 mm
R_{iris} = 41 mm
Nb thick. = 3.8 mm

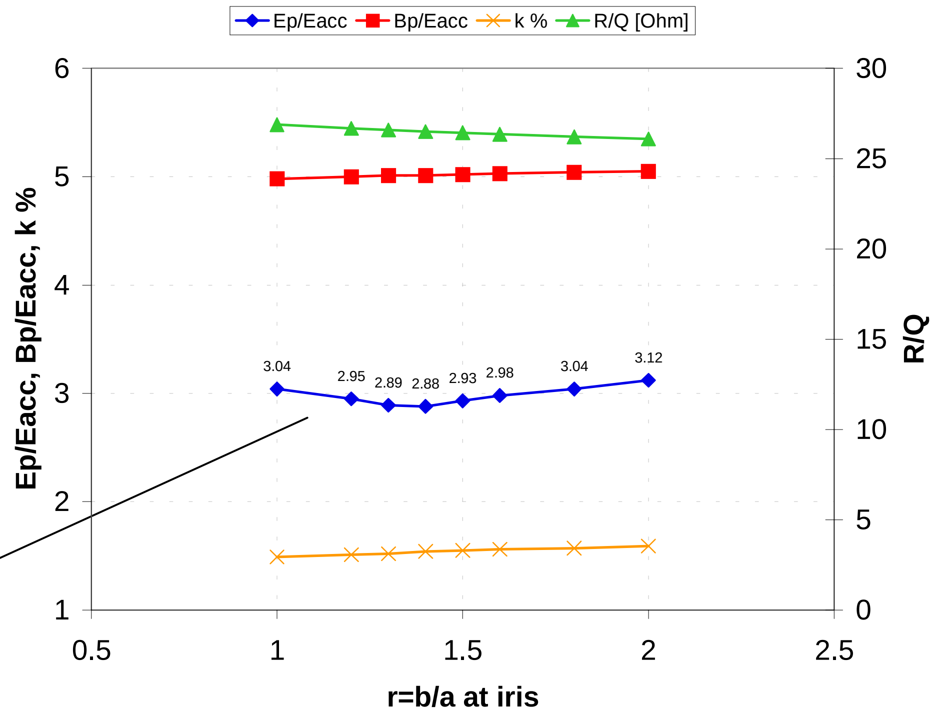
Note on KL values

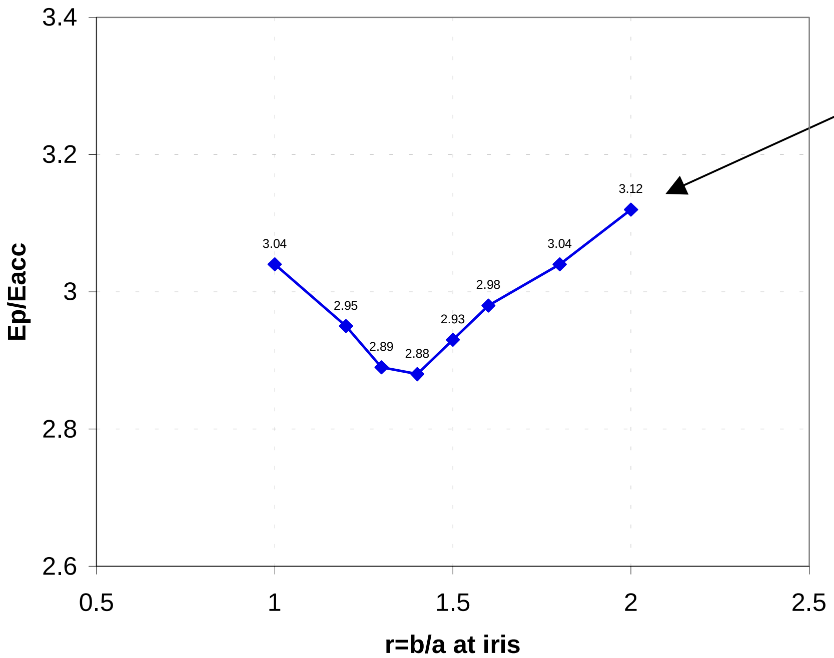
- As a figure of merit for the Lorentz forces, to compare the effect on different cavities, we use the coefficients computed for two reference stiffening ring radius: 80 mm and 70 mm.
- These are not necessarily the minimal values, as shown by the following curve, but the final position should be left free, for example to tune the vibrational mode shift!



Optimal value for r...

- The iris ellipse aspect ratio has always an optimal value that minimized the peak surface E field
- All the other cavity parameters are unchanged





Reference data

L = 56.8 mm
R = 1.5
α = 7°
d = 8 mm
R_{iris} = 41 mm
Nb thick. = 3.8 mm

... with no influence on mechanic

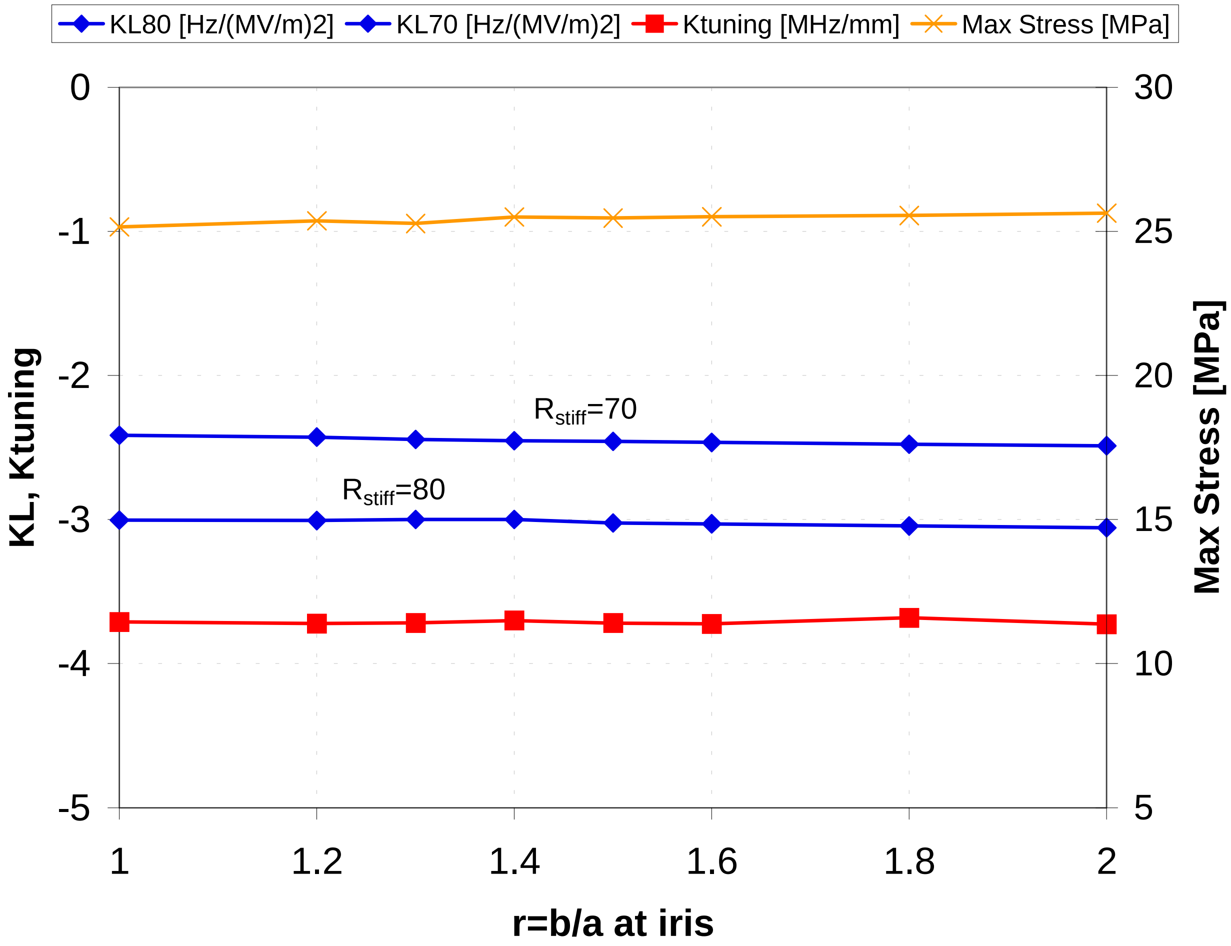
- The mechanic behavior of the stiffened cavity is insensible to the iris aspect ratio

- Maximum von Mises stresses are referred to a 2 bar external pressure

- Constant stiffening ring radius set at two referrence values:
  - •Rstiff = 70 mm
  - •Rstiff = 80 mm

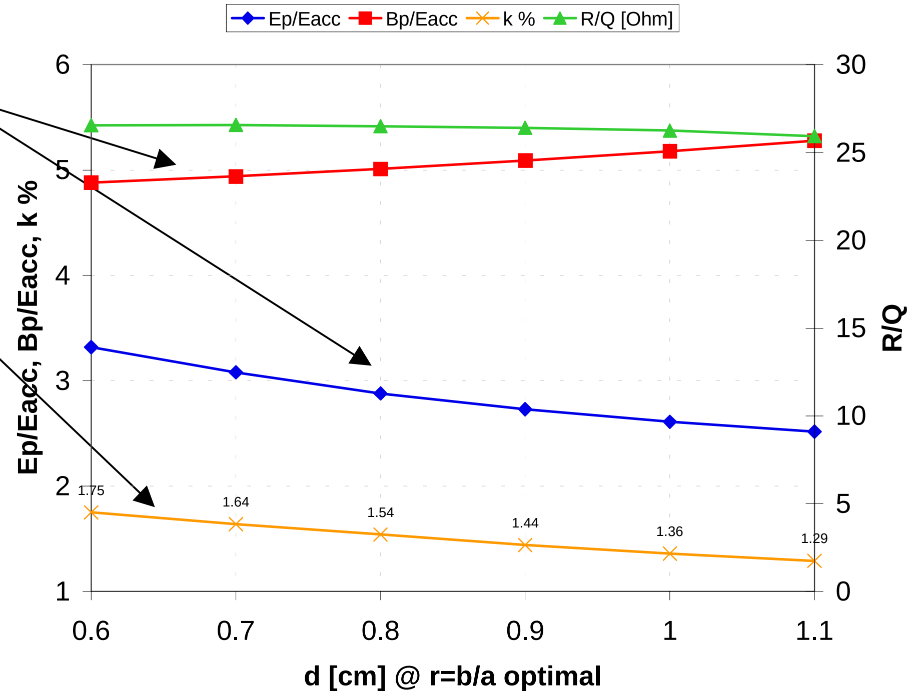
Reference data

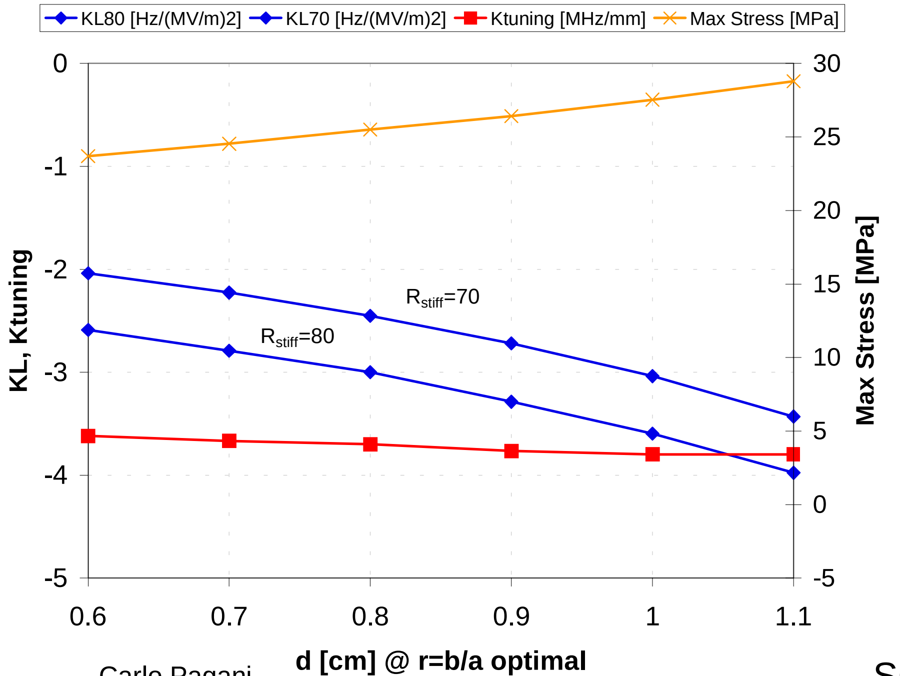
L = 56.8 mm
R = 1.5
$\alpha = 7°$
d = 8 mm
R_{iris} = 41 mm
Nb thick. = 3.8 mm



Influence of d @ constant R_{iris}

- d can be used to balance the electric and magnetic volumes of the cavity
  - The value of r is always optimal.
  - The cell to cell coupling changes, if Riris is kept constant





Better mechanical performances are reached with decreasing d

Reference data

L = 56.8 mm
R = 1.5
α = 7°
r = optimal
R_{iris} = 41 mm
Nb thick. = 3.8 mm

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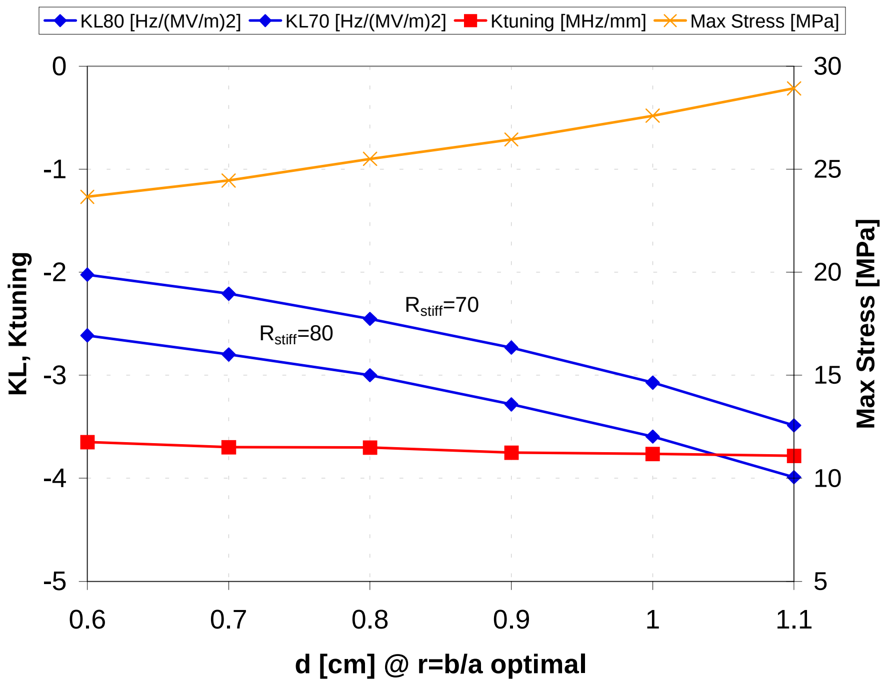
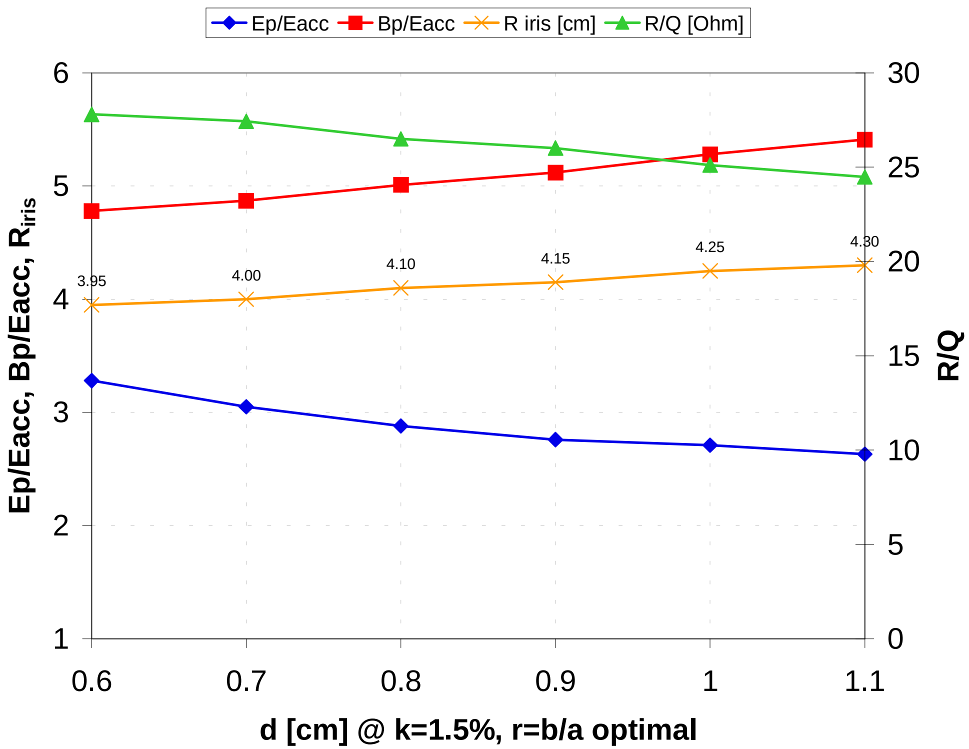
TJNAF, April 2000

Influence of d @ constant k

- If we want to keep a constant cell to cell coupling we have to adjust Riris





Better mechanical performances are reached with decreasing d

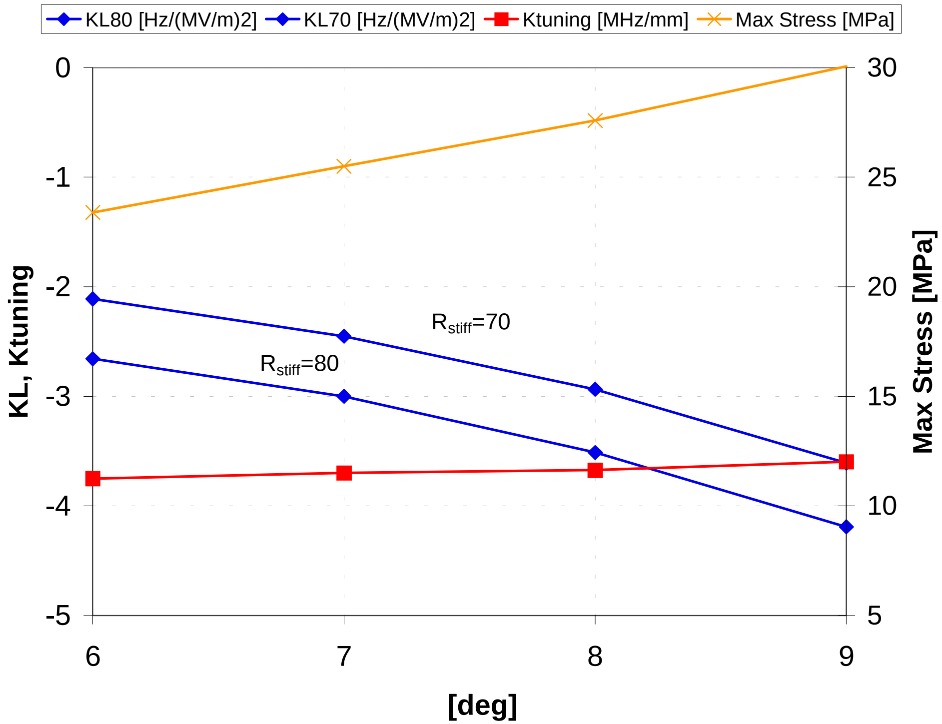
Reference data

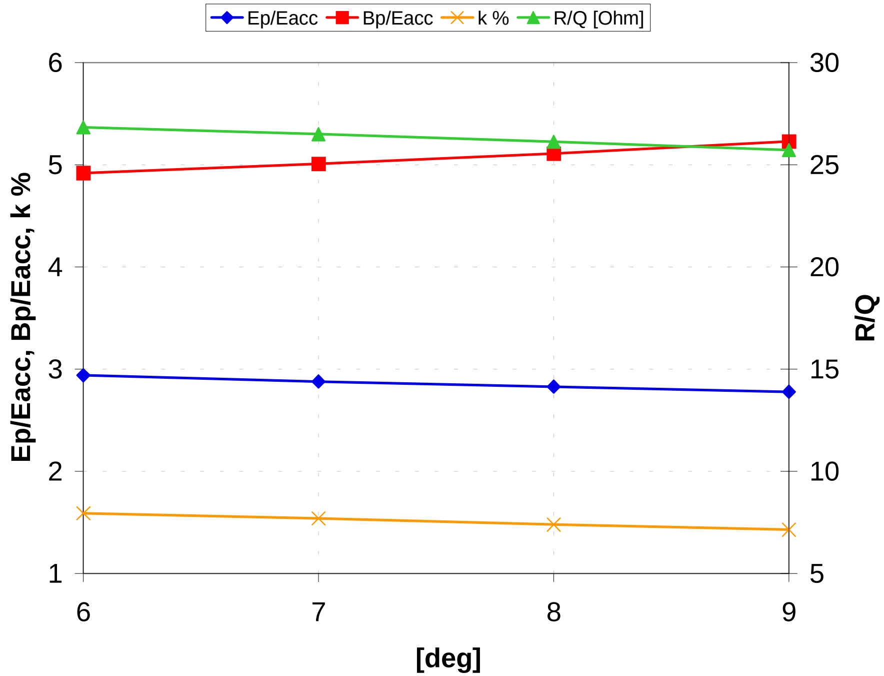
L = 56.8 mm
R = 1.5
α = 7°
r = optimal
k = 1.5%
Nb thick. = 3.8 mm

Dependence on α

The wall angle α slightly affects all the e.m. Parameters, but has a strong effect on the mechanical performances:

- Lower values are preferred for Lorentz force detuning
- Too small α could be critical for chemistry and cleaning



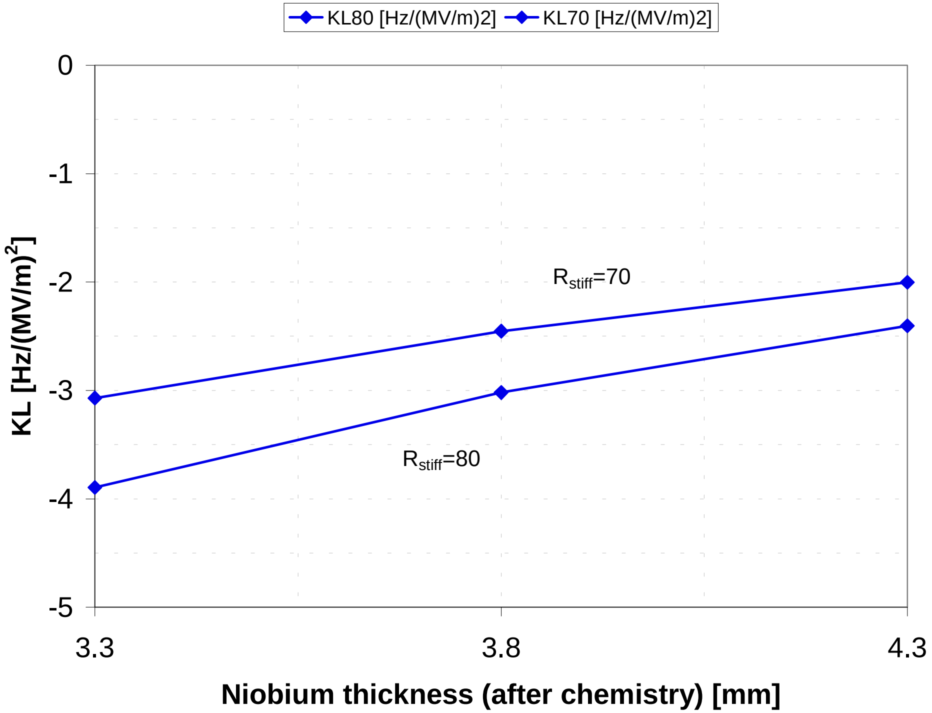


Reference data

L = 56.8 mm
R = 1.5
r = optimal
d = 8 mm
k = 1.5%
R_{iris} = 41 mm
Nb thick. = 3.8 mm

Niobium thickness

- As expected Niobium thickness highly affects the Lorentz Force detuning coefficient KL
- Niobium thickness should be limited because of:
  - Material cost
  - Shaping difficulties
  - Tuning forces
- Nb sheet thickness is supposed to be 200 μm larger than the value used for calculations



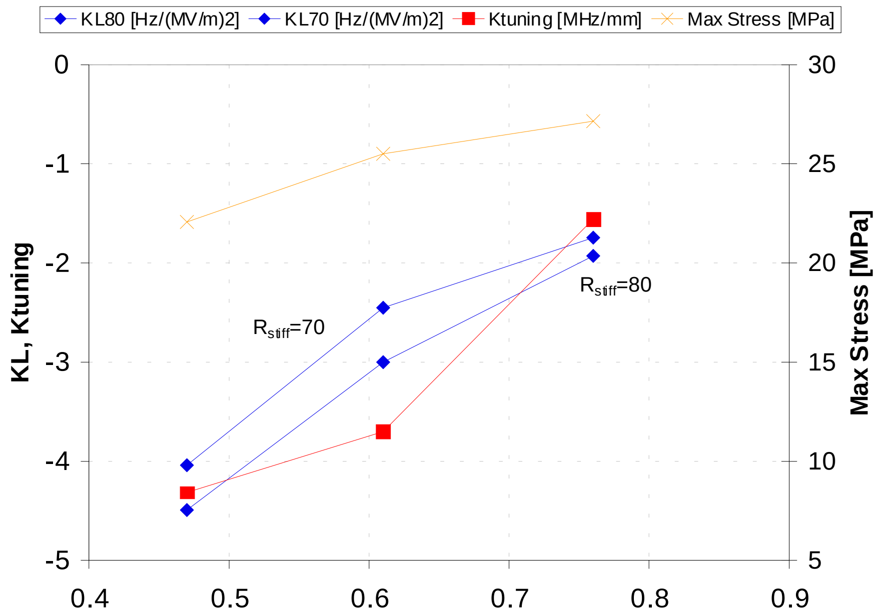
Reference data

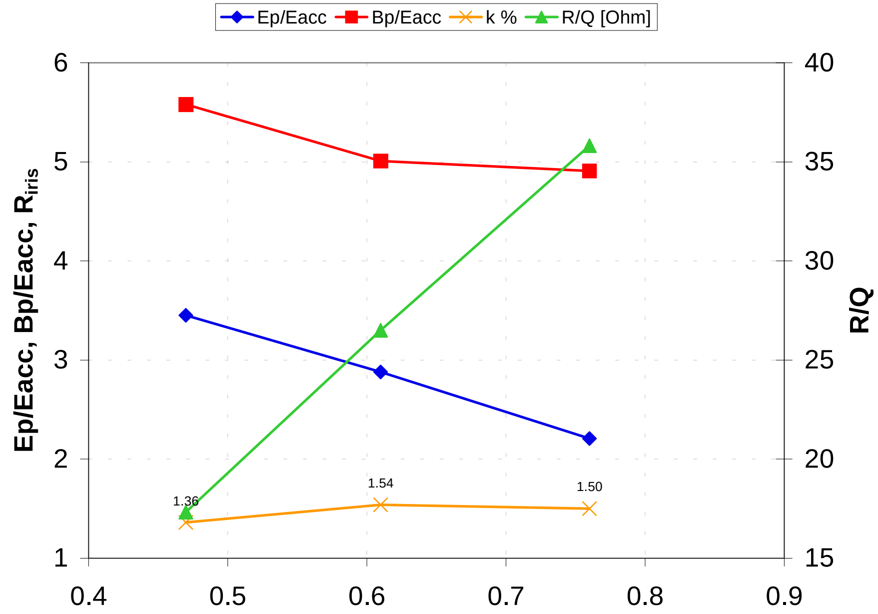
L = 56.8 mm
R = 1.5
r = 1.4
d = 8 mm
k = 1.5%
R_{iris} = 41 mm

A Nb sheet thickness of 4 mm (i.e 3.8 mm after treatments) represents a reasonable compromisese for the β = 0.61 Cavity

Cavity cell length ⇔β

- Shortening the cavity cell length it is more difficult to fullfill the Lorentz detuning requirements, and a price for providing the necessary cavity stiffening is paid on the peak surface fields





- Increasing the cavity cell length the peak surface field can be lowered, being easier to provide the Lorentz forces stiffening

Mechanical analysis of the half cells

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- A postprocessor reads the SFO output and builds a FEM model of the cell shape using the field values for
  - Radiation pressure calculation (Lorentz forces)
  - Evaluation of the Slater coefficients on the cavity profile and on the iris plane (for computing the frequency shift due to cavity deformations)
- An automated ANSYS™ procedure performs all the following calculations
  - Three boundary conditions for Lorentz forces load cases, trying 15 different positions of the stiffening ring between R_{iris} and D
    - free cell length
    - fixed cell length
    - cell with semirigid helium vessel/stiffening system
  - 2 bar vacuum load on the cavity
  - Tuning sensitivity (N/Hz, N/mm, Hz/mm)

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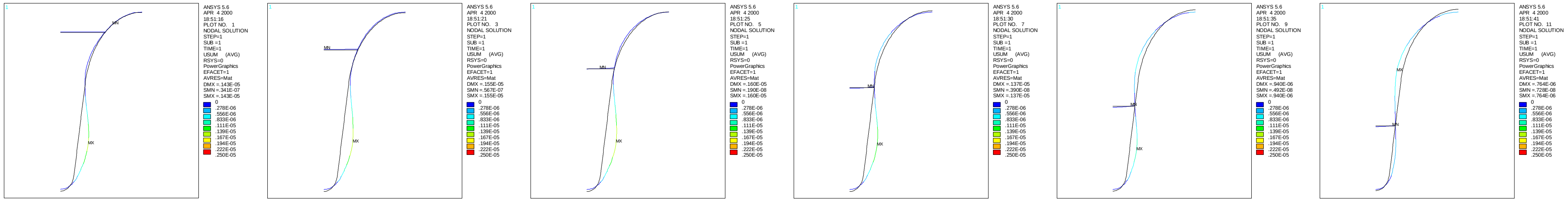
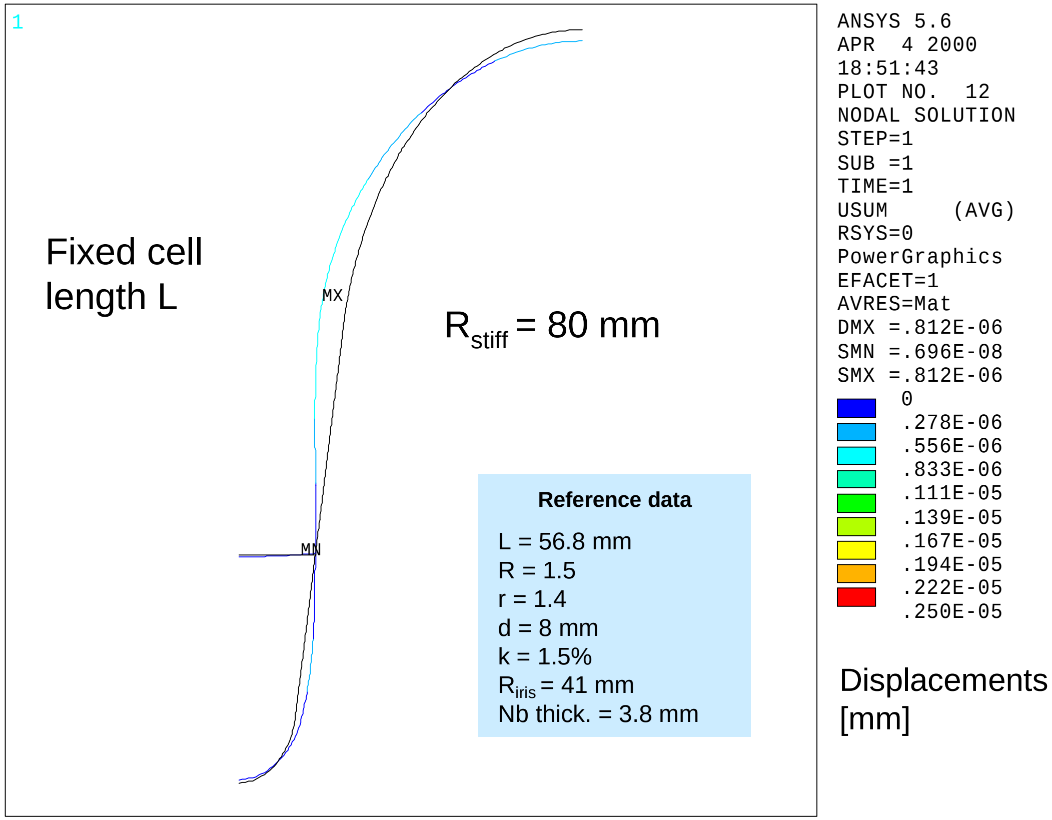
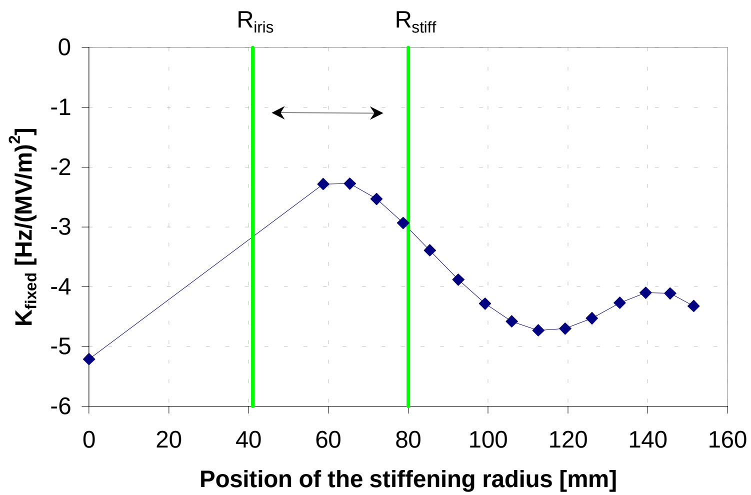
TJNAF, April 2000

Optimal stiffening ring position



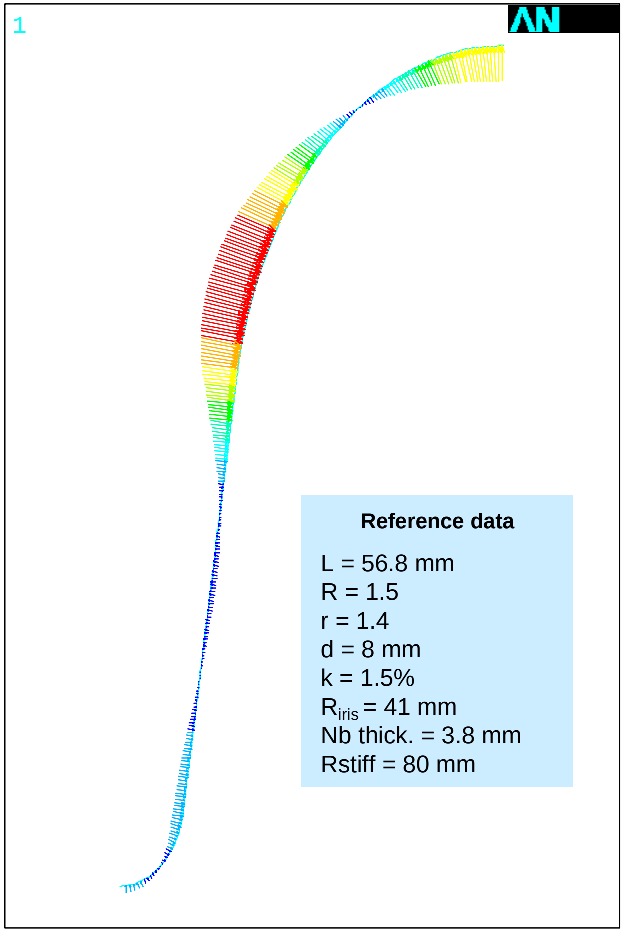


The Lorentz forces coefficients for 15 different stiffening ring positions are evaluated automatically with ANSYS, preparing the geometry and reading the fields from the SFO output from SUPERFISH

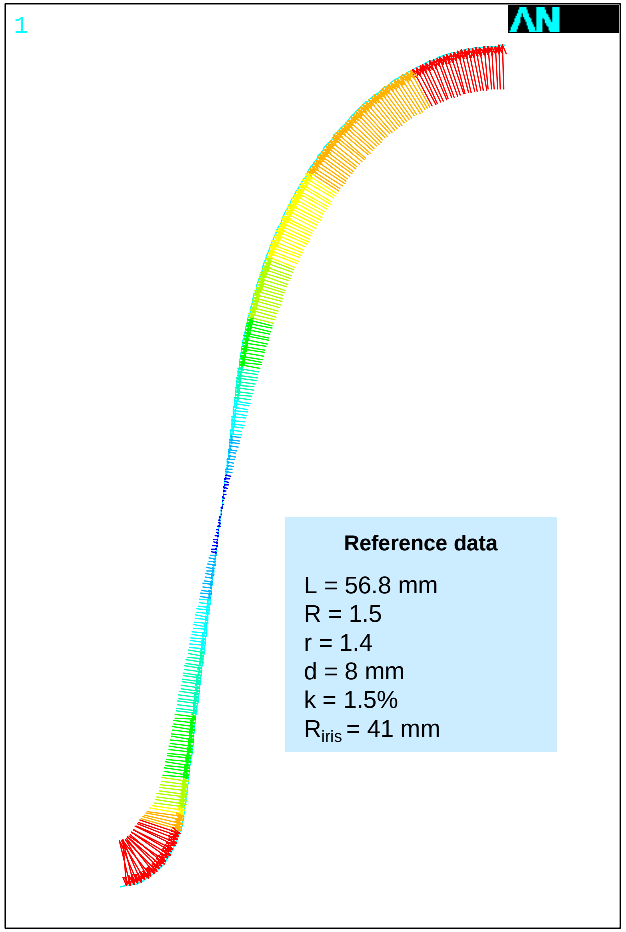


Contributions to the Lorentz Detuning

Local contributions to the frequency shift



Slater integral for a unitary displacement



KL for different boundary conditions

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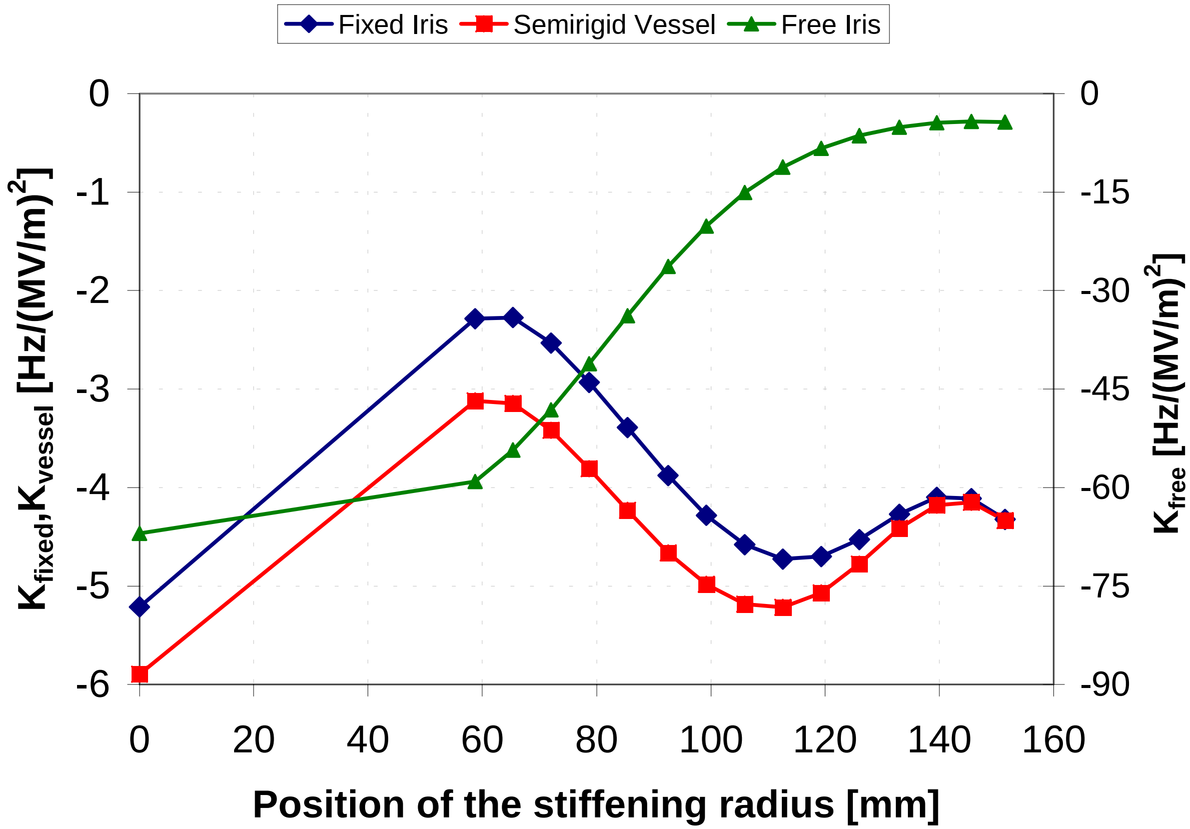
- The estimate for KL strongly depends on the cell boundaries. We compute it for 3 different cases:
  - Fixed cell length
  - Free cell length
  - Helium Vessel/Tuning System (= 3 tubes with diameter 30 mm and thickness 2 mm)



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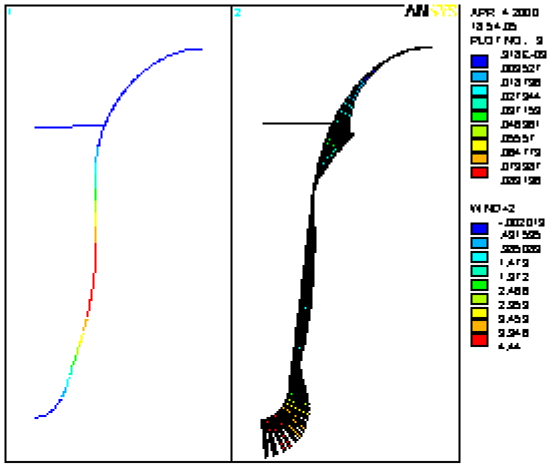
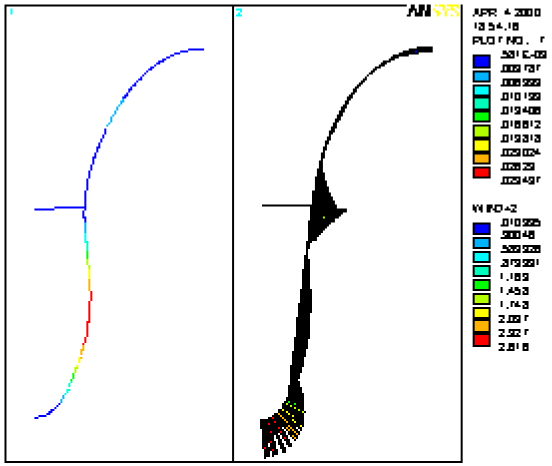
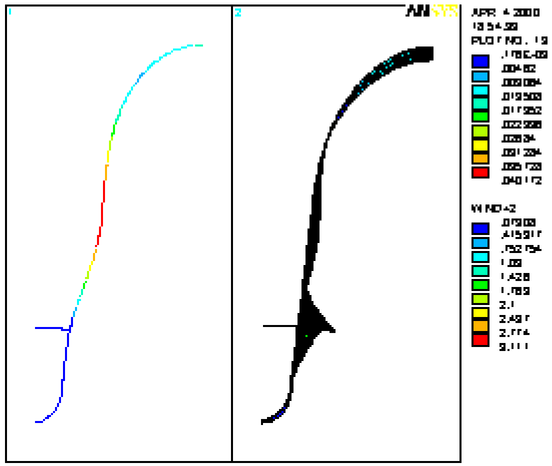
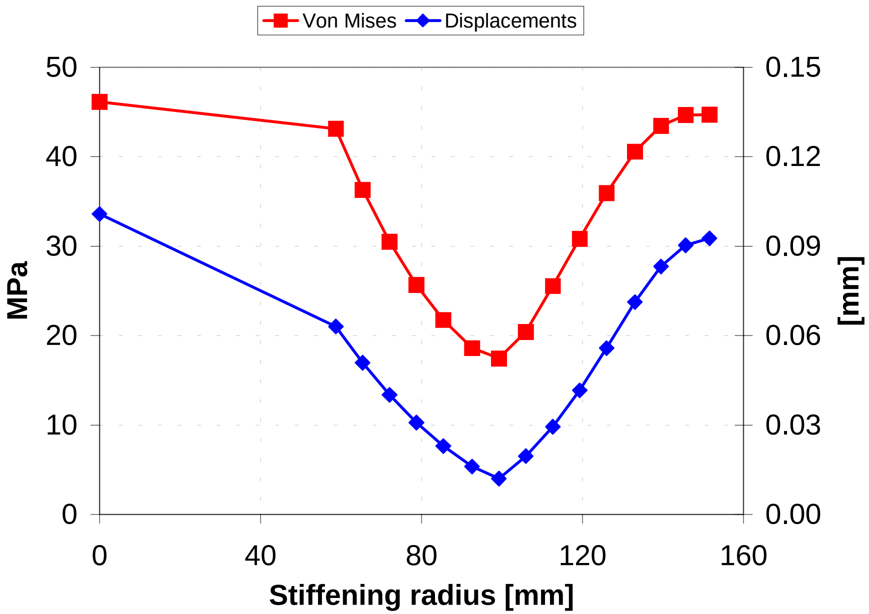
Vacuum load (2 bar)

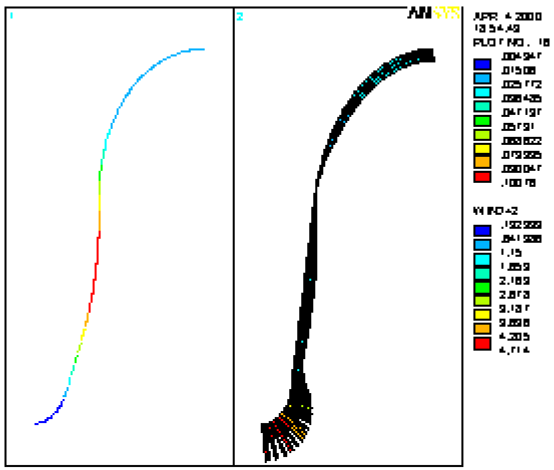








Vacuum load calculations are performed with 2 bar differential pressure, for all stiffening cases (and the unstiffened cavity)



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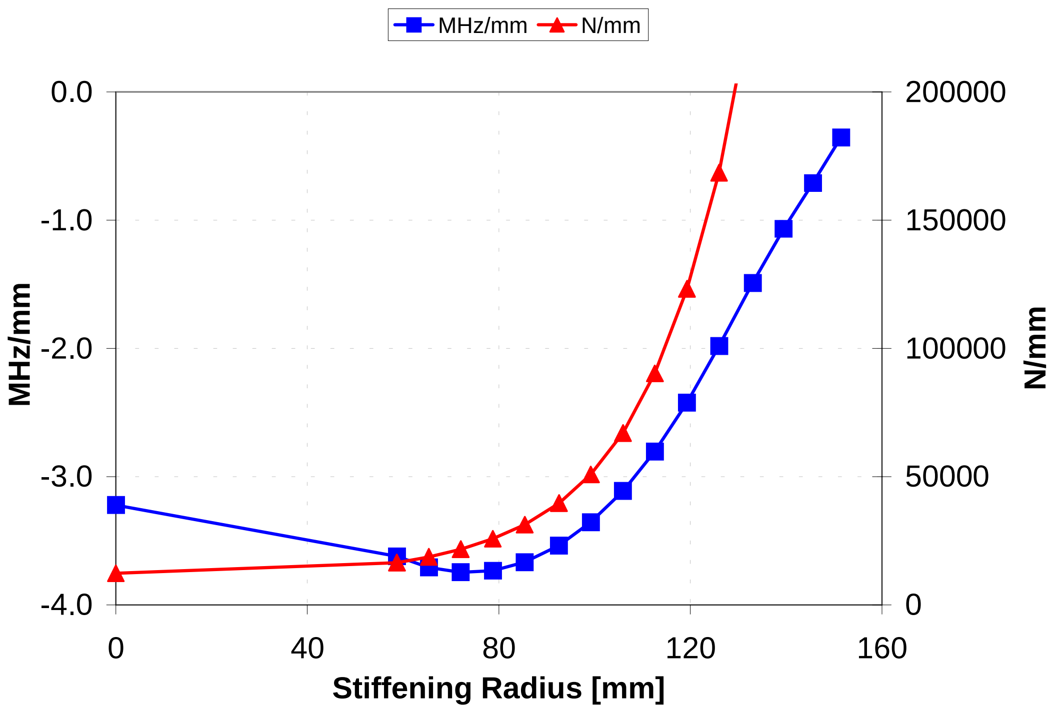
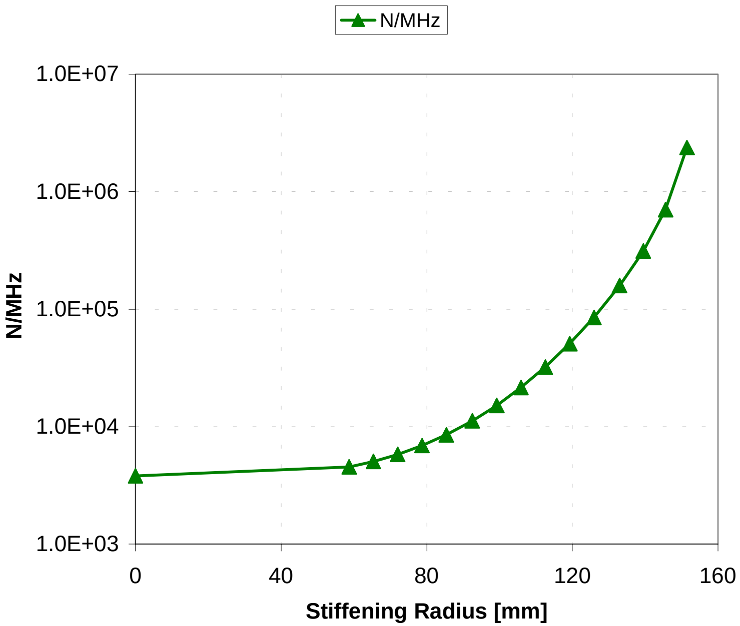
Tuning sensitivity

- The tuning sensityvity is computed shortening the stiffened cell by 1 mm at the iris and computing
  - The frequency displacement
  - The force needed
  - The net force per MHz displacement



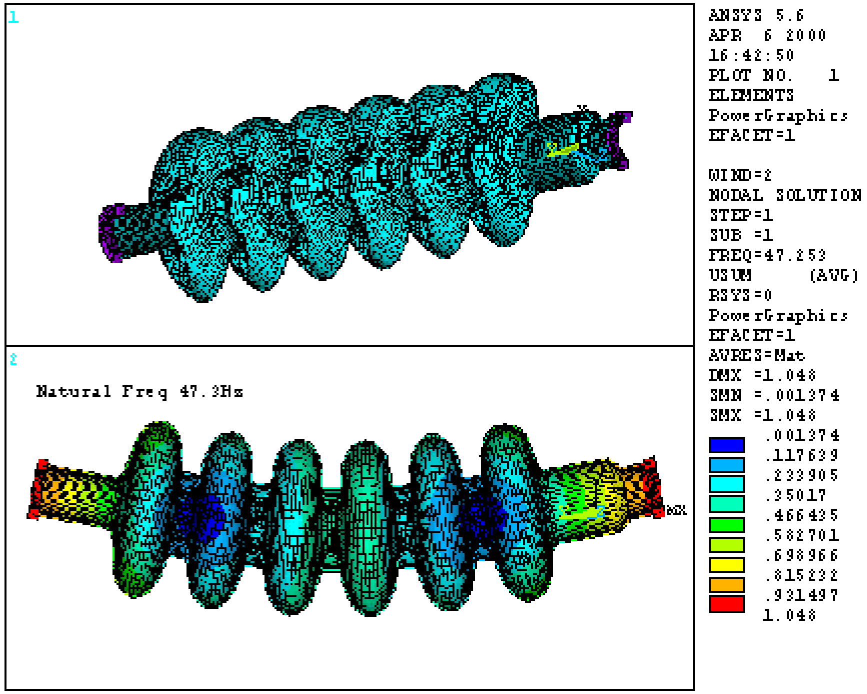


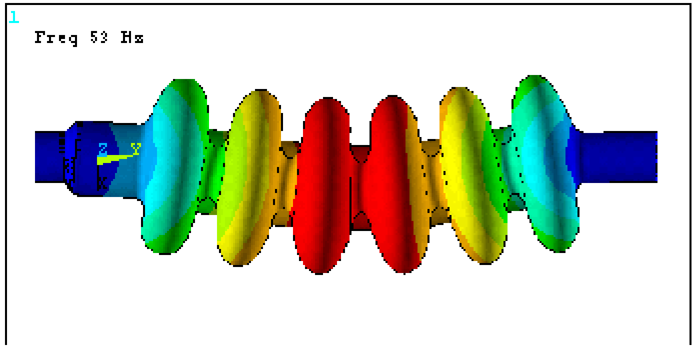
Mechanical Analysis of the cavity

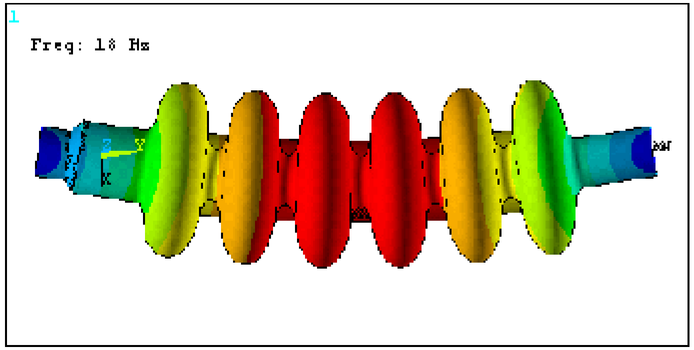
- Calculation of the vibration eigenmodes of the 3D structure
  - The eigenmodes can be calculated easily, but the results (especially for the transverse ones) are strongly influenced by the constraints and the boundary conditions set by the ancillary components like helium tank, tuner system, supports, coupler, ...
  - This consideration imply that it is **impossible** to give reliable figures of the true mechanical eigenfrequencies!
  - *But, because of the high Q of these modes, we can define suitable strategies to shift the frequencies of the dangerous modes, either longitudinal and transverse.*
- First we calculate the vibration eigenmodes of the “completely free” cavity
- Then we look at their dependence from a suitable external knob:
  - Helium vessel fixtures for the transverse modes
  - Stiffening ring radius for longitudinal modes

Natural transverse eigenmode (β=0.76)

- Natural frequencies of the β=0.76 cavity under 3 conditions:
  - Free cavity (47 Hz) – Left
  - Fully constrained flanges (53 Hz) – Top Right
  - Longitudinal constrained (hinged) flanges (18 Hz) – Bottom Right

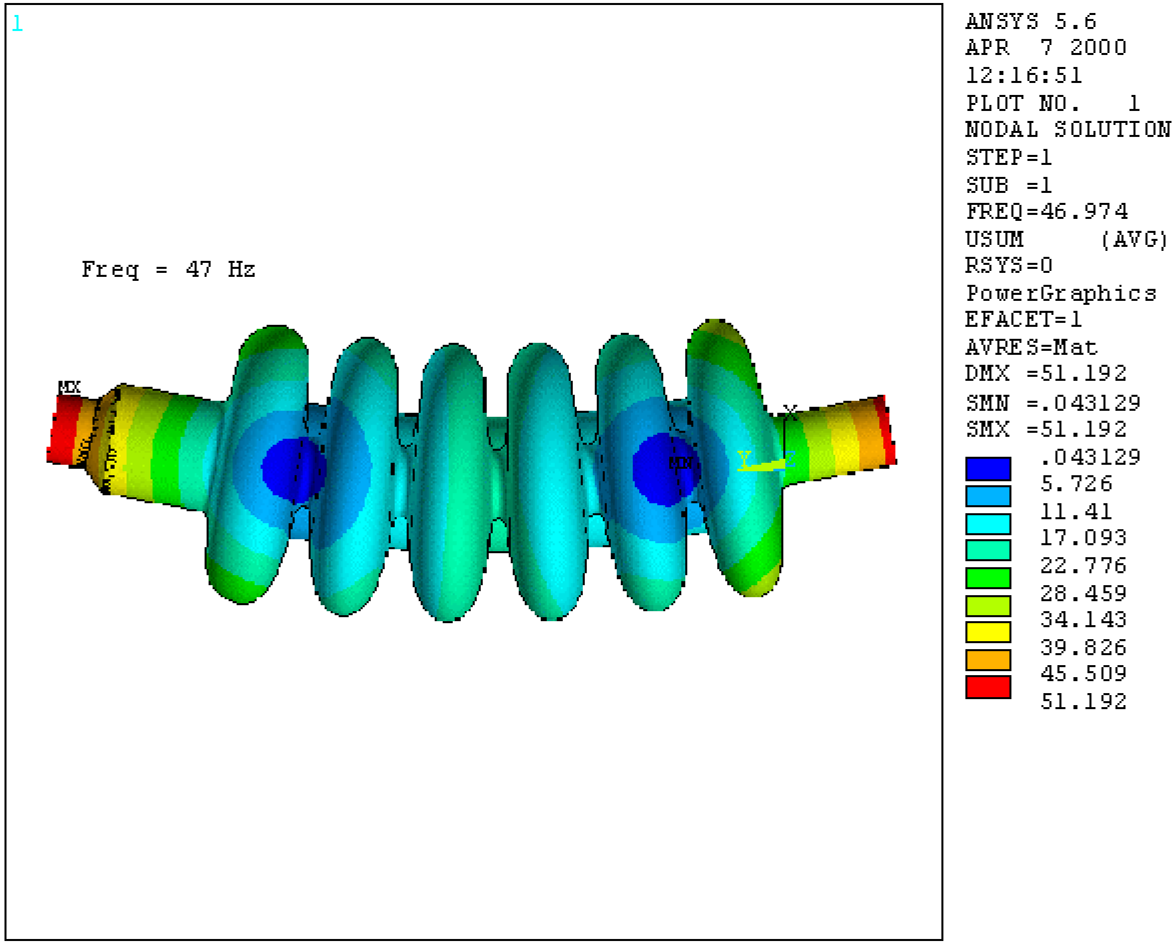






Natural transverse eigenmode (β=0. 61)

Natural frequency of the “free” β=0.61 cavity: 47 Hz



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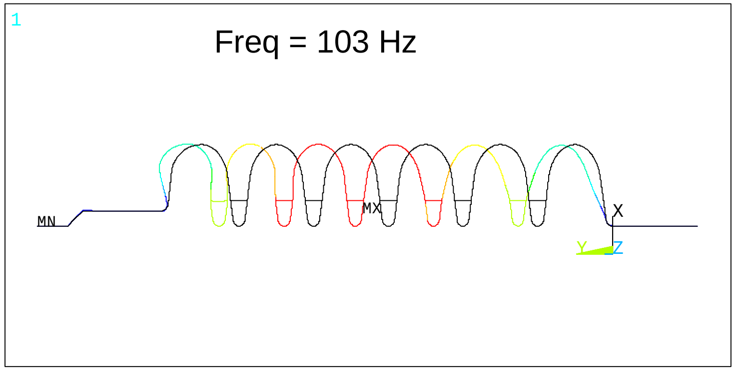
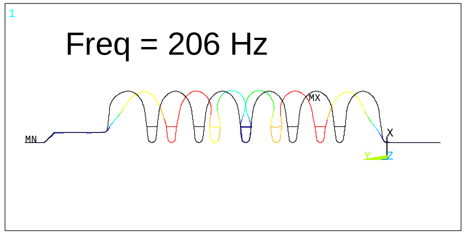
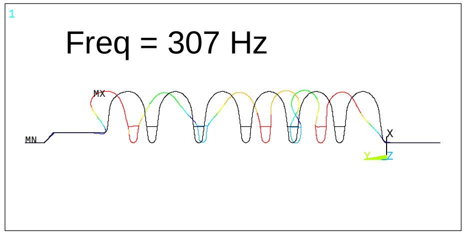
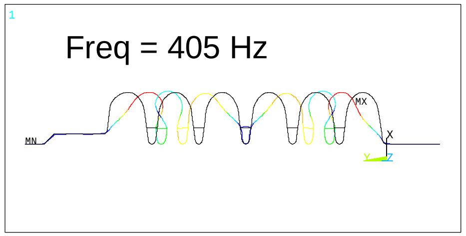
Longitudinal modes of the β=0.61

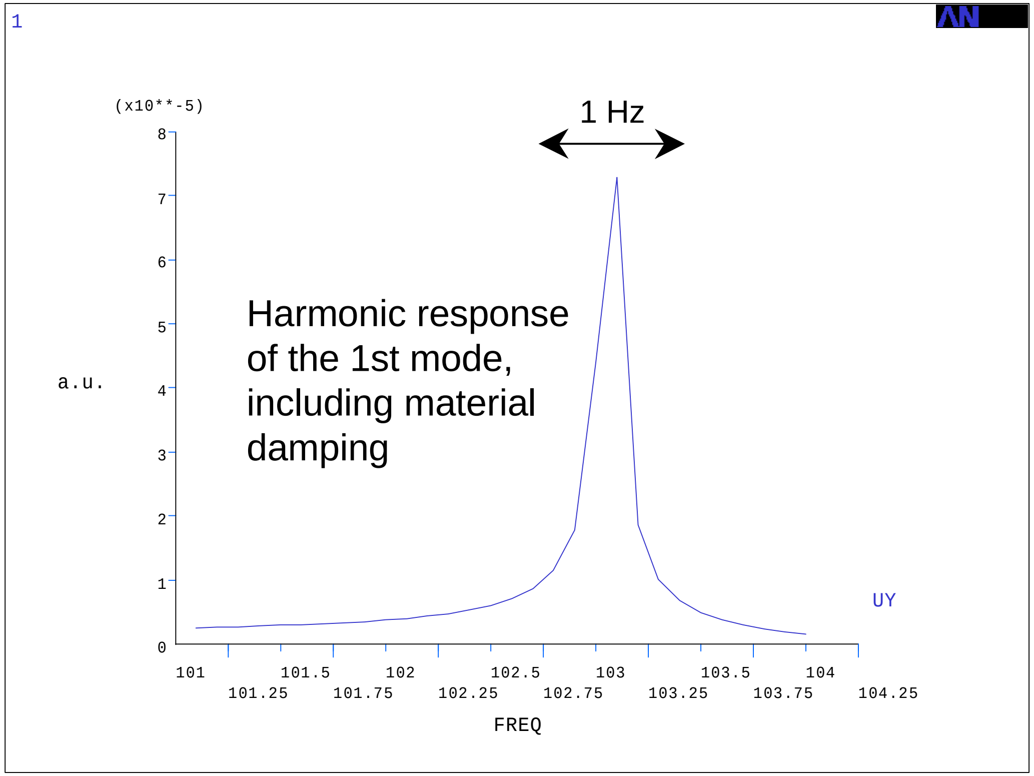






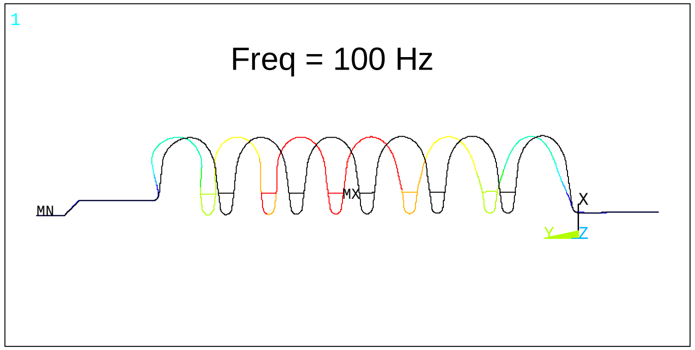


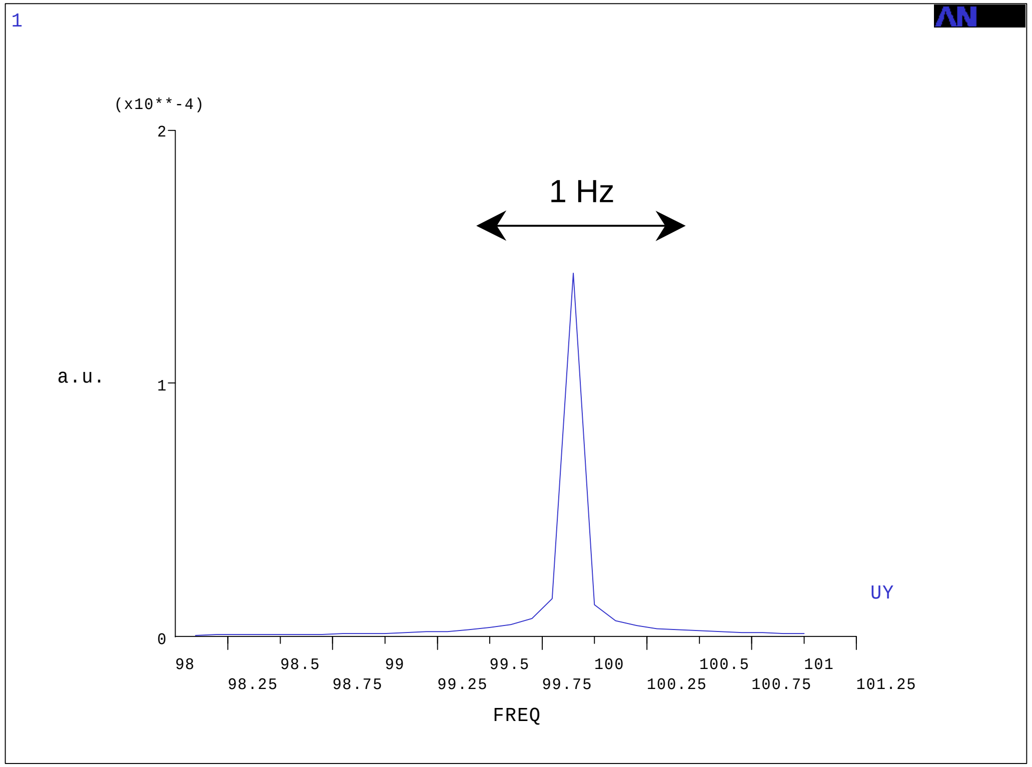
- First 4 modes of the β=0.61 cavity
- These longitudinal modes are almost independent from the constraints conditions imposed on the model



Shift of the Longitudinal modes

- Slightly changing the stiffening radius we can move the longitudinal modes (here we shifted R_{stiff} towards the axis by 5 mm)
- The frequency changed from 103 to 100 Hz

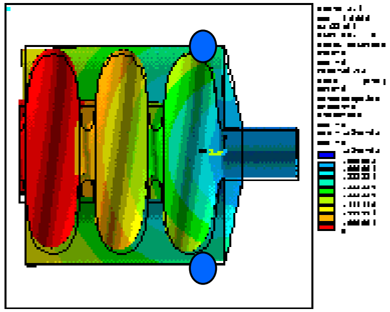




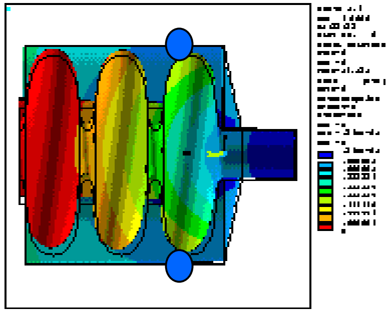
Shift of the transverse modes

- Control of the frequency of the transverse modes can be achieved moving the cavity fixtures positions, as shown in the following sequence for the lowest frequency mode of the β=0.61 cavity

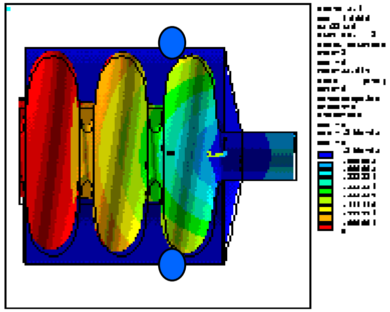
Freq = 48.7 Hz



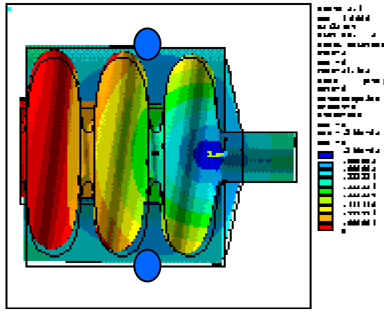
Freq = 46.5 Hz



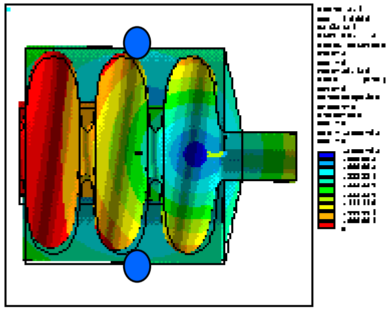
Freq = 45.9 Hz



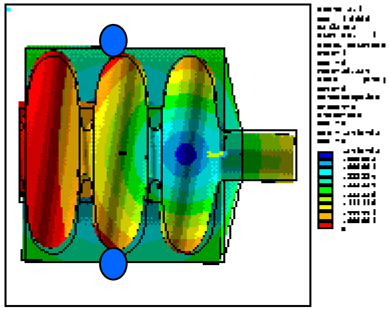
Freq = 46.9 Hz



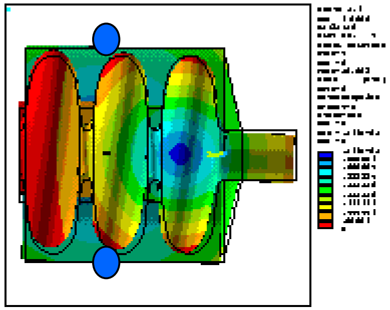
Freq = 48.7 Hz



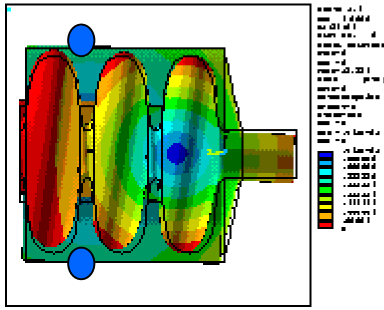
Freq = 50.4 Hz



Freq = 52.0 Hz



Freq = 53.3 Hz



Black dots show the longitudinal position of the external fixtures

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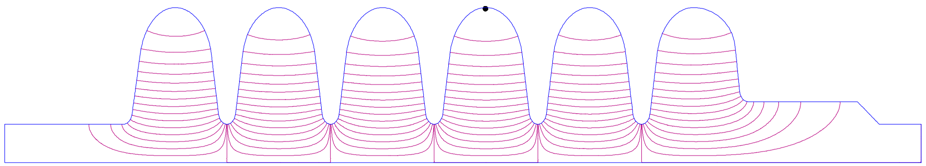
β_g = 0.61 Cavity: Possible compromise - 1

Effective β that matches the TTF curve = 0.630

E_p/E_{acc}	2.97 (2.88 inner cell)
B_p/E_{acc} [mT/(MV/m)]	5.2
R/Q [Ω]	299
G [Ω]	214
k [%]	1.54
Q_{BCS} @ 2 K [10^9]	33.2
Frequency [MHz]	805.082
Field Flatness [%]	1



KL70 = -2.4 [Hz/(MV/m)^2] KL80 = -3.0 [Hz/(MV/m)^2]

Nb thickness = 3.8 mm

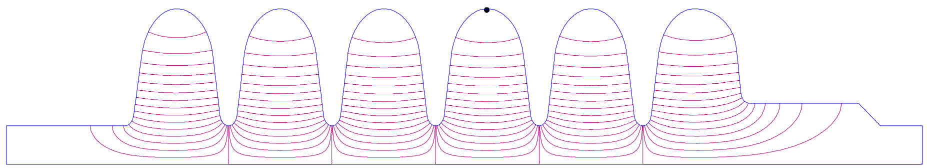
Geometrical Parameters

	Inner cell (DB 627)	End Cell Left	End Cell Right (coupler)
L [mm]	56.8	56.8	60.0
R_{iris} [mm]	41.0	41.0	65.0
D [mm]	165.36	165.36	165.36
d [mm]	8.0	8.0	8.0
r	1.4	1.4	1.4
R	1.5	1.6	1.0
α [deg]	7.0	7.919	5.948

β_g = 0.61 Cavity: Possible compromise - 2

Effective β that matches the TTF curve = 0.630

E_p/E_{acc}	2.97 (2.88 inner cell)
B_p/E_{acc} [mT/(MV/m)]	5.2
R/Q [Ω]	299
G [Ω]	214
k [%]	1.54
Q_{BCS} @ 2 K [10^9]	33.2
Frequency [MHz]	805.082
Field Flatness [%]	1



KL70 = -2.0 [Hz/(MV/m)²] KL80 = -2.5 [Hz/(MV/m)²]

Nb thickness = 3.8 mm

Geometrical Parameters

	Inner cell (DB 616)	End Cell Left	End Cell Right (coupler)
L [mm]	56.8	56.8	56.8
R_{iris} [mm]	41.0	41.0	65.0
D [mm]	165.36	165.36	167.00
d [mm]	8.0	8.8	8.0
r	1.4	1.4	1.3
R	1.0	1.1	1.0
α [deg]	7.0	7.919	7.0

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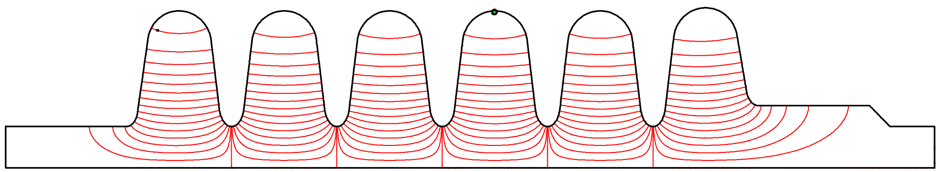
The β_g = 0.61 Cavity for SNS – 4 dies

Effective β that matches the TTF curve = 0.630

E_p/E_{acc}	2.72 (2.63 inner cell)
B_p/E_{acc} [mT/(MV/m)]	5.73 (5.44 inner cell)
R/Q [Ω]	279
G [Ω]	214
k [%]	1.53
Q_{BCS} @ 2 K [10^9]	27.8
Frequency [MHz]	805.000
Field Flatness [%]	2



KL70 = -2.9 [Hz/(MV/m)^2] KL80 = -3.4 [Hz/(MV/m)^2]

Nb thickness = 3.8 mm

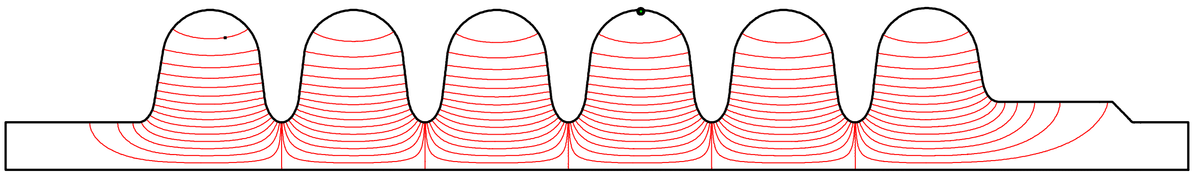
Geometrical Parameters

	Inner cell	End Cell Left	End Group (coupler) Left	End Group (coupler) Right
L [mm]	56.8	56.8	56.8	
R_{iris} [mm]	43.0	43.0	43.0	65.0
D [mm]	163.76	163.76	166.98	
d [mm]	11.0	11.0	11.0	10.0
r	1.7	1.5	1.7	1.5
R	1.0	1.0	1.0	
α [deg]	7.0	8.36	7.0	10.0

The β_g = 0.81 Cavity for SNS – 4 dies

Effective β that matches the TTF curve = 0.810

E_p/E_{acc}	2.19 (2.14 inner cell)
B_p/E_{acc} [mT/(MV/m)]	4.79 (4.58 inner cell)
R/Q [Ω]	484.8
G [Ω]	233
k [%]	1.52
Q_{BCS} @ 2 K [10^9]	36.2
Frequency [MHz]	805.004
Field Flatness [%]	1.1



KL70 = -0.7 [$Hz/(MV/m)^2$] KL80 = -0.8 [$Hz/(MV/m)^2$]

Nb thickness = 3.8 mm

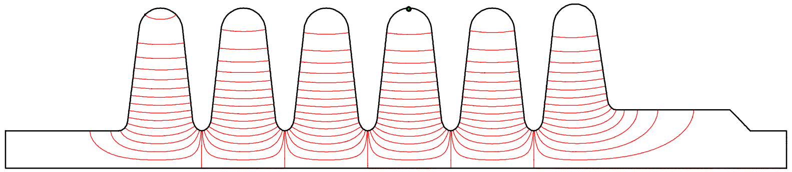
Geometrical Parameters

	Inner cell	End Cell Left	End Group (coupler) Left	End Group (coupler) Right
L [mm]	75.5	75.5	75.5	
R_{iris} [mm]	48.8	48.8	48.8	70.0
D [mm]	164.15	164.15	166.11	
d [mm]	15.0	13.0	15.0	13.0
r	1.8	1.6	1.8	1.6
R	1.0	1.0	1.0	
α [deg]	7.0	10.072	7.0	10.0

The Proposed β_g = 0.47 Cavity for RIA – 4 dies

Effective β that matches the TTF curve = 0.488

E_p/E_{acc}	3.41 (3.26 inner cell)
B_p/E_{acc} [mT/(MV/m)]	6.92 (6.47 inner cell)
R/Q [Ω]	160
G [Ω]	137
k [%]	1.50
Q_{BCS} @ 2 K [10^9]	21.2
Frequency [MHz]	805.006
Field Flatness [%]	1.8



KL70 = -3.3 [Hz/(MV/m)^2]   KL80 = -3.3 [Hz/(MV/m)^2]

KL70 = -1.8 [Hz/(MV/m)^2]   KL80 = -1.8 [Hz/(MV/m)^2]

Nb thickness = 4.8 mm

Nb thickness = 6.15mm

Geometrical Parameters

	Inner cell	End Cell Left	End Group (coupler) Left	End Group (coupler) Right
L [mm]	**43.9**	**43.9**	**43.9**	
R_{iris} [mm]	**38.6**	**38.6**	**38.6**	**60.0**
D [mm]	**164.56**	**164.56**	**168.84**	
d [mm]	**8.5**	**8.0**	**8.5**	**8.0**
r	**1.45**	**1.3**	**1.45**	**1.3**
R	**1.0**	**1.0**	**1.0**	
α [deg]	**6.5**	**7.2**	**6.5**	**9.0**